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RESEARCH AND TECHNOLOGY ORGANISATION

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RTO TECHNICAL REPORT **TR-HFM-122**

Tactile Displays for Orientation, Navigation and Communication in Air, Sea and Land Environments

(Les systèmes d'affichage tactiles pour l'orientation, la navigation et la communication dans les environnements aérien, maritime et terrestre)

This document is the Final Report of Task Group RTO-TR-HFM-122.

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Edited by

J.B.F. van Erp and B.P. Self

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RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

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- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

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HFM-122 Membership List

CHAIRMAN

Dr. Jan B.F. VAN ERP
Chief Scientist Department Human Interfaces
TNO Human Factors
Kampweg 5, PO Box 23
3769 ZG Soesterberg
NETHERLANDS
Email: jan.vanerp@tno.nl

Dr. William ALBERY
AFRL/HEPA
2800 Q Street, Bldg 24
Wright Patterson AFB, OH 45433-7947
USA
Email: balbery@specpro-inc.com

Asst. Prof. J. Christopher BRILL
Michigan Technological University
Dept of Cognitive and Learning Sciences
1400 Townsend Drive
Houghton, MI 49931
USA
Email: cbrill@mtu.edu

Mr. Otto W. CARLANDER
Swedish Defence Research Agency (FOI)
Division of Man System Interaction
Dept of Information Presentation
P.O. Box 1165
SE-581 11 Linköping
SWEDEN
Email: otto.carlander@foi.se

Dr. Robert CHEUNG
Defence Research & Development Canada
Leader – Performance Group
Individual Readiness Section
1133 Sheppard Ave. W.
P.O. Box 2000
Toronto, Ontario M3M 3B9
CANADA
Email: bob.cheung@drdc-rddc.gc.ca

Prof.dr. Roger W. CHOLEWIAK
Princeton University (retired)
12 Allwood Drive
Lawrenceville
NJ 08648
USA
Email: rcholewi@Princeton.edu

Dr. Trevor DOBBINS
Human Sciences and Engineering
5 The Terrace, Mill Lane, Sidlesham
Chichester, West Sussex PO20 7NA
UNITED KINGDOM
Email: trevor.dobbins@humansci-eng.com

Mrs. Maaike DUISTERMAAT
Department Human Interfaces
TNO Human Factors
Kampweg 5
3769 ZG Soesterberg
NETHERLANDS
Email: maike.duistermaat@tno.nl

Dr. Linda ELLIOTT
Research Psychologist
Human Research and Engineering Directorate
Army Research Laboratory
US Army Infantry Center, Bldg 4, Room 33
Fort Benning, GA 31905
USA
Email: linda.r.elliott@us.army.mil

Mr. Bill ERCOLINE
Manager, San Antonio Operations
Wyle Laboratories AFRL/HEM
2485 Gilllingham Dr., Bldg 170
Brooks City-Base, TX 78235-5104
USA
Email: bill.ercoline@brooks.af.mil

Mr. Lars M. ERIKSSON
Senior Scientist
Swedish Defence Research Agency, FOI
Div. of Command and Control Systems
Dept. of MSI Man-System Interaction
P.O. Box 1165
SE-581 11 Linköping
SWEDEN
Email: lars.eriksson@foi.se

Dr. Kristen LIGGETT
Air Force Research Laboratory
Human Effectiveness Directorate AFRL/HECI
2210 Eighth Street
Wright Patterson AFB, OH 45433-7511
USA
Email: kristen.liggett@wpafb.af.mil

Dr. Braden McGRATH
Ball Solutions Group
80 Northbourne Ave
Braddon ACT 2612
AUSTRALIA
Email: bmcgrath@ballsolutions.com

Mr. Andy McKINLEY
Biomedical Engineer
Biobehavioral Performance Branch
Human Effectiveness Directorate
Air Force Research Laboratory
2215 First Street, Bldg 33
Wright-Patterson AFB, OH 45433-7947
USA
Email: Andy.McKinley@wpafb.af.mil

Dr. Brian P. SELF (Co-Editor)
Associate Professor
Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo, CA 93407-0358
USA
Email: bself@calpoly.edu

Mr. Gary ZETS
Engineering Acoustics, Inc.
Email: Zets@eaiinfo.com

Tactile Displays for Orientation, Navigation and Communication in Air, Sea and Land Environments

(RTO-TR-HFM-122)

Executive Summary

Tactile displays such as vibrating mobile phones present information via the user's skin. Tactile displays may reduce the risks of sensory and cognitive overload and can increase the operational effectiveness of military personnel. This report aims to disseminate basic knowledge on tactile displays, to share the lessons learned from previous research, and to provide future research directions. It is intended to be useful for both designers and end users.

Many issues must be considered in the design and application of tactile displays. The psychophysics of tactile cues are described in Chapter 2 and must be examined to ensure the success of any new tactile display. Sensation thresholds, spatial and temporal summation, adaptation, and tactile illusions are major design considerations and affect the perception of tactile cues. Primary perceptual issues for tactile applications include the spatial acuity of the torso (or other applicable body part), the ability to localize the stimulus, and the perception of the stimulus external direction based on that stimulus localization. Human factors concerning these perceptual issues are discussed in Chapter 3. Other human factors, including coding principles, cognitive issues, and multi-sensory integration, are also introduced. When presenting new displays, there is always the danger of both sensory and cognitive overload. It is therefore important to provide intuitive display information whenever possible, and to avoid tactile clutter. Because it is anticipated that tactile displays will be combined with other display modalities, it is essential to determine how tactile signals can best augment visual and/or auditory signals. Familiarization with the cueing principles discussed in Chapter 3 should provide guidance on how to program multi-sensory and/or multifunction displays.

The type of hardware utilized depends on the specific application for the display – hardware issues are discussed in Chapter 4. Electrical tactors can be very small and lightweight, but are extremely dependent on skin condition (e.g., dry versus wet) and tactor contact. Rotary-inertial tactors are very cost effective, robust, and do not require much power, while linear actuators yield high force and displacement. Pneumatic tactors may be the best choice when there is a ready supply of compressed air, such as in a fighter jet. Finally, future developments in electro-active polymers and micro-electro-mechanical systems (MEMS) may result in other attractive options for display designers.

The tactor system chosen must operate in a wide variety of environments and integrate well with the current life support ensemble of the user. Chapter 5 describes the different types of environments which may affect tactile displays, including temperature extremes, underwater immersion, whole body vibration, high sustained acceleration, and microgravity. Integration issues such as skin-tactor contact, the weight and power requirements of the entire system, compatibility with emergency egress and ditching, and of course comfort are also discussed in the chapter.

The multitude of issues may seem rather large to those just beginning research in the area of tactile displays. Although factors such as stimulus intensity, environmental stressors, tactor type, and perceptual characteristics must be considered, one must remember that a simple suprathreshold tactile stimulus can

easily serve an alerting function, and that the location of that stimulation is intuitively obvious. The successes of various tactile displays discussed in Chapter 6 are all built upon this basic premise. We conclude with the statement that that data described in this report are important evidence that using the tactile modality in military environments can improve performance and lessen workload, thereby improving the quality and safety of the man-machine-interface and the operational effectiveness of military personnel.

Les systèmes d'affichage tactiles pour l'orientation, la navigation et la communication dans les environnements aérien, maritime et terrestre

(RTO-TR-HFM-122)

Synthèse

Les systèmes d'affichage tactiles, tels que les téléphones portables vibrants, présentent les informations à l'utilisateur par voie cutanée. Les systèmes d'affichage tactiles peuvent réduire les risques de surcharge sensorielle et cognitive et améliorer l'efficacité opérationnelle du personnel militaire. Ce rapport a pour but de dispenser des connaissances de base sur les systèmes d'affichage tactiles, de partager les leçons tirées des précédentes recherches et de fournir des instructions pour les recherches futures. Il est destiné à servir à la fois aux concepteurs et aux utilisateurs finaux.

De nombreuses questions doivent être examinées lors de la conception et de l'application de systèmes d'affichage tactiles. La psychophysique des repères tactiles est décrite dans le Chapitre 2 et doit être étudiée pour assurer le succès de tout nouveau système d'affichage tactile. Les seuils de sensation, la sommation spatiale et temporelle, l'adaptation et les illusions tactiles sont des considérations majeures de conception et affectent la perception des repères tactiles. Les principaux problèmes de perception relatifs aux applications tactiles concernent notamment l'acuité spatiale du torse (ou de toute autre partie du corps applicable), la capacité à localiser le stimulus, et la perception de la direction externe du stimulus basée sur la localisation de ce stimulus. Les facteurs humains concernant ces problèmes de perception sont exposés dans le Chapitre 3. Les autres facteurs humains, notamment les principes de codage, les questions cognitives et l'intégration multisensorielle, sont également présentés. Lors de l'introduction de nouveaux systèmes d'affichage, il existe toujours le risque d'une surcharge à la fois sensorielle et cognitive. Il est donc important de fournir des informations intuitives sur le système d'affichage à chaque fois que cela est possible, et d'éviter les signaux tactiles parasites. Dans la mesure où il est prévu que les systèmes d'affichage tactiles seront combinés à d'autres modalités d'affichage, il est essentiel de déterminer la manière dont les signaux tactiles pourront augmenter de façon optimale les signaux visuels et/ou auditifs. La familiarisation avec les principes de repérage évoqués dans le Chapitre 3 devrait fournir des indications sur la programmation des systèmes d'affichage multisensoriels et/ou multifonctions.

Le type de matériel utilisé dépend de l'application spécifique du système d'affichage – les questions de matériel sont abordées dans le Chapitre 4. Les tacteurs électriques peuvent être légers et de très petite taille, mais sont extrêmement dépendants de l'état de l'épiderme (sec ou humide, par exemple) et du contact du tacteur. Les tacteurs à inertie rotative sont très rentables, robustes et consomment peu d'énergie, alors que les actionneurs linéaires ont une grande force de déplacement. Les tacteurs pneumatiques peuvent s'avérer le meilleur choix lorsque l'on dispose d'une réserve d'air comprimé, comme dans un avion de chasse. Pour finir, les développements futurs des polymères électroactifs et des systèmes micro-électro-mécaniques (MEMS) pourraient fournir d'autres options intéressantes aux concepteurs de systèmes d'affichage.

Le système de tacteur choisi doit pouvoir fonctionner dans de nombreux environnements et s'intégrer à l'ensemble de l'équipement de vie actuel de l'utilisateur. Le Chapitre 5 décrit les différents types d'environnements pouvant affecter les systèmes d'affichage tactiles, notamment les températures extrêmes, l'immersion sous-marine, la vibration globale du corps, une forte accélération soutenue et la

micrograviité. Les questions d'intégration, telles que le contact épiderme-tacteur, les exigences de poids et d'alimentation de l'ensemble du système, la compatibilité avec les évacuations d'urgence et les amerrissages forcés, et bien sûr le confort, sont également abordées dans ce chapitre.

La multitude de sujets peut sembler relativement impressionnante à ceux qui entament à peine des recherches dans le domaine des systèmes d'affichage tactiles. Bien que des facteurs tels que l'intensité du stimulus, les facteurs de stress environnementaux, le type de tacteur et les caractéristiques de la perception doivent être pris en considération, il faut garder en mémoire qu'un simple stimulus tactile supraliminaire suffit à alerter, et que la localisation de cette stimulation est intuitivement évidente. Le succès de divers systèmes d'affichage tactiles étudiés dans le Chapitre 6 s'est toujours fondé sur ce principe de base. En conclusion, nous déclarons que les données décrites dans ce rapport prouvent largement que le recours à la modalité tactile dans les environnements militaires peut augmenter la performance et réduire la charge de travail, améliorant ainsi la qualité et la sécurité de l'interface homme-machine et l'efficacité opérationnelle du personnel militaire.

Chapter 1 – INTRODUCTION TO TACTILE DISPLAYS IN MILITARY ENVIRONMENTS

by

J.B.F. van Erp and B.P. Self

Challenging situations, such as those encountered by military pilots, are often a major thrust for ergonomic innovation. Examples include the development of advanced, multimodal, and intuitive interface techniques to counteract the danger of visual, auditory, and cognitive overload. Tactile displays (displays that use the skin as an information channel) typically belong to this category. The variety of tactile displays ranges from a single vibrating element (like those in mobile phones) to matrices of elements covering the torso of a pilot, soldier, diver, or other operator. Examples of this matrix display are the TNO Tactile Torso Display (TTTD, see Figure 1.1) and the Naval Aeromedical Research Laboratory Tactile Situation Awareness System (TSAS), which both provide intuitive three-dimensional spatial information.

Figure 1.1: A Helicopter Pilot Showing a TNO Tactile Torso Display (TTTD), Consisting of a Matrix of Vibrating Elements Inside a Multi-Ply Garment Covering the Pilot's Torso.

1.1 JUSTIFICATION FOR THIS EFFORT

1.1.1 Timeliness

This report is a work item of the NATO RTO HFM Task Group 122 "Tactile displays for orientation, navigation and communication in air, sea, and land environments". Objectives of this group were to define critical research issues, to disseminate knowledge and to provide operational guidelines; all of these serve the goal of increasing NATO's successful operations by incorporating tactile displays in advanced human-system interfaces.

There is an increasing number of research efforts focused on applying tactile interfaces for orientation, navigation, and communication. The technology, although initially focused on pilots, is recognised as relevant to land and sea systems as well, including but not limited to divers, dismounted soldiers, UAV operators, and boat and armoured vehicle drivers. Many laboratory and field studies have shown that tactile displays can improve operator performance and reduce operator workload (e.g., [1]).

Given the current progress of technological developments and operational concepts regarding the use of tactile displays in military environments, a strong and combined effort of NATO countries is essential to resolve the unique human-system issues associated with effective applications of tactile displays. Relevant issues include hardware/actuator technology, perception and psychophysics, interface and coding standardisation, operating concepts, and integration with life-support equipment and visual and auditory displays. This report focuses on the aspects important from a NATO Human Factors and Medicine (HFM) panel point of view. However, the task group stresses the need to review progress and to share understanding of the important technical developments and to guide research efforts and standardisation issues across a broad set of NATO participants and NATO RTO panels. The timeliness of NATO's interest in tactile display and standardisation is underlined by the establishment of an ISO working group on tactile and haptic interaction in November 2005 [2].

Despite the fast growing interest in tactile displays, the field is relatively young. The justification for this work is primarily based on the following:

- Tactile displays are pre-eminently 'purple', i.e., applications are being developed for Navy, Army, Air Force and Special Forces.
- Because the field is relatively young and the number of NATO countries involved in the technology is still limited, disseminating knowledge may have a large impact on countries not yet involved. Contrary to the small steps taken in long-standing technologies, these countries can make a large leap forward in this field.
- The same argument holds for industry.
- Because many applications are still in a developmental state, NATO is in a position to easily set standards for design, applications, and use.

1.1.2 Why use Tactile Displays?

There have been several drivers for research groups to start developing tactile display applications, including the eminent need to provide spatial disorientation (SD) countermeasures and solutions to the threats of sensory and/or cognitive overload.

1.1.2.1 Spatial Disorientation Countermeasure

The development and implementation of tactile displays as an SD countermeasure is supported by the conclusion of the NATO Research & Technology Organisation symposium; 'Spatial disorientation in

military vehicles: causes, consequences and cures' held in 2002. In the executive summary, it was stated that: *'The most important advance of recent years with the potential to combat spatial disorientation has been the use of tactile stimuli to give information on spatial orientation'* [3]. SD is a serious threat to military/civilian pilots and aircraft and is a substantial detriment to military aviation operations in terms of cost, lives lost, and mission degradation. Mishap analyses indicate that SD is an important causal factor in aviation accidents, especially for rotary wing operations, and are more deadly than mishaps attributed to other factors. Accurate data on the involvement of SD are critical in the development of aviation safety technologies that have the highest and most cost effective potential to reduce these mishaps. Considerable effort has been put into SD countermeasures such as training programmes and advanced (visual) cockpit displays [4] [5]. Adding tactile orientation displays to this list of countermeasures has the potential to reduce the number of aviation related SD mishaps.

1.1.2.1.1 Mishaps Statistics and Cost Benefit Analysis

To underline the importance of the initial thrust to develop tactile displays as a countermeasure to spatial disorientation, some mishap statistics are given below. The definition of SD as given by the Air Standard Coordination Committee (ASCC) AIR STD 61/117/07 is the following; "*Spatial Disorientation is used to describe a variety of incidents occurring in flight where the pilot fails to sense correctly the position, motion, or attitude of the aircraft or of himself within the fixed co-ordinate system provided by the surface of the earth and the gravitational vertical*". Previous studies have cited the potential for misclassification and underreporting of SD as a causal factor in mishaps.

- US Air Force

Mishaps related to SD in the United States Air Force (USAF) accounted for approximately 21% of all USAF serious mishaps during the 1980's and 90's, and 39% of all fatal incidents between 1991 and 2000. SD costs the Department of Defence over $300 million per year in accident investigations, family compensation, and aircraft reconstruction. "On average, the USAF loses five aircraft with aircrews (and sometimes with passengers) each year due to spatial disorientation, and most of these are related to loss of attitude awareness" [6], p. 489). Between October 1993 and September 2002, accidents related to spatial disorientation cost the Air Force 243 aircraft, 310 lives, and approximately $6.23 billion. In this timeframe, there were 25 high performance fighter or attack mishaps where spatial disorientation was identified as a causal or contributing factor. These mishaps resulted in 19 fatalities and cost the Air Force over $455 million. The continued incidence and seriousness of spatial disorientation has prompted researchers to seek new methods to both predict spatial disorientation and to counteract it.

- US Army

According to Braithwaite [7], SD was the primary contributing factor in 43% of all US Army rotary-wing (helicopter) aircraft accidents. The average lives lost per accident were nearly three times greater for SD accidents (0.38) than for non-SD accidents (0.14) (Braithwaite et al., 1998). SD was a significant factor in 291 (30%) of Class A, B, and C helicopter accidents in the US Army between 1987 and 1995. One hundred ten lives were lost and a cost of $468 million was incurred [8].

- US Navy

Using Naval Safety Center (NSC) AIR STD 61/117/07 classification, 12% of class A mishaps were classified as SD mishaps. Using the ASSC definition, 22% of the class A mishaps could be classified as SD mishaps. The breakdown of rotary wing versus fixed wing SD mishaps was 29% and 18%, respectively. SD mishaps claimed lives 63% of the time versus 28% for non-SD mishaps. Night operations appear to be an important factor, with two-thirds of all SD mishaps occurring at night. In the time frame FY97 to FY02, 47 rotary wing mishaps (rate 1.94 per 100,000 flight hours) occurred, with 14 classified as SD mishaps (rate 0.58 per 100,000 flight hours). These SD mishaps resulted in 35 deaths and $118 million costs. In the same time frame, 120 fixed wing aircraft occurred (rate 1.81 per 100,000 flight hours) with

22 classified as SD mishaps (0.33 per 100,000 flight hours). These SD mishaps resulted in 23 deaths and $475 million costs [9].

- Cost-benefits analysis for tactile countermeasures

Using the mishap data presented above, tactile display mishap prevention analysis data, the projected flight hours, and the tactile display development and procurement costs, a cost-benefit analysis to equip the US Navy H-60 helicopter fleet with a TSAS system was performed. With an initial investment of capital (R&D funds) of $20M, the 5 year internal rate of return was estimated at 4%. This corresponds to the avoidance of two H-60 mishaps and the saving of approximately 8 lives [10].

1.1.2.2 Counteracting the Threat of Sensory and Cognitive Overload

A second important motivation for the application of tactile displays is the threat of sensory and/or cognitive overload in current man-machine interfaces. Although visual displays are usually easy to comprehend, the development of computer driven displays provides the opportunity to provide a vast quantity of information that can overload the individual's capacity to process the information provided. Warnings and procedures have been issued to avoid this, starting with the system's design stage [11][12]. The threat of sensory overload makes designers of human- machine interfaces increasingly apply multi-modal interfaces. An important reason for this is the need for an alternative or complementary information channel in complex operator environments [13]. Traditionally, the auditory channel is considered as an alternative or supplement to visual displays. Examples include the presentation of route navigation [14][15] and tracking error information ([16]; for a review see [17], pp. 480 – 481). However, there are situations in which the visual and auditory channels of an operator are both heavily loaded or in which the visual and/or auditory information is degraded or not available. Examples include:

- Operators in complex environments who work at the limits of their visual and auditory processing capacity, such as pilots [18][19].
- Operators whose visual or auditory attention is preferably focused on a specific area of interest, such as car drivers who need to concentrate on the road [20][21][22]), and dismounted soldiers who want to focus on the environment and possible threats.
- Operators who work in a visually or auditorily deprived environment, such as remote operators [23][24]), virtual environment users [25], divers in dark waters, and drivers of fast boats.
- Operators who work under conditions that require minimization of the transmission of light or sound, as during night or covert operations.

In these situations, it may be beneficial to employ a tactile display.

In addition to sensory overload, an operator may experience cognitive overload. One example of this involves navigation information in cars, which may result in an over demand of the (momentarily available) cognitive capacities of the driver. Evaluation has shown that visual in-vehicle information systems may negatively influence the drivers' scanning behaviour and attention allocation (i.e., they distract the driver). A possible effect is that the driver is temporarily out of the loop. There is a general belief that driver overload and distraction resulting from the actions of in-vehicle support systems can form a threat to the positive effects expected from these systems (e.g. [26][27][28]; see also Wickens, 2006). Warnings and procedures have been issued to avoid this, starting with the system's design stage [11]. In cockpit applications, visual displays have a specific disadvantage when presenting three dimensional (3D) navigation information. Because the displays are flat or 2D, one (or more) dimensions must be compressed. This results in loss of information and usually requires a cognitive component to reconstruct the 3D picture from the 2D display. An example is a 2D planar display depicting a bird's eye view of a set of waypoints while the altitude is displayed alphanumerically.

In Chapter 3, we will further discuss why employing tactile displays may be a solution to lessen the threats of sensory and cognitive overload.

1.2 POTENTIAL APPLICATIONS

The number of current and potential applications in which tactile displays are employed is still growing. A short overview is provided in the section below. The applications that are within the scope of this report are further elaborated in Chapter 6.

Information Presented by Tactile Displays

- Spatial orientation cues: gravity vector indication to reduce SD, particularly under conditions of sustained acceleration, absence of external visual cues, and high cognitive workload.
- Navigation cues: way-point direction cues, no-go areas, obstacle avoidance cues, collision avoidance information.
- Vehicle control: course control, turbulence, helicopter drift (especially imperceptible movement indications where visual cues are absent; e.g. helicopter drift whilst hovering in white/brown out conditions).
- Directional warning and attention allocation: threat indications, indicating areas of (visual) interest, ground proximity warnings.
- Spatial information/Situation Awareness support: direction of wingman, points of interest, group members, enemy contact, line of attack.
- Synthetic environments: reproducing or simulating perceptual cues of remote or virtual worlds (e.g., in controlling Uninhabited Military Vehicles) and in training and simulation.
- Communication:
  - a) Non-visual communication especially under the following conditions: bright light environment where visual display screens are difficult to comprehend, scenarios where vision is required for primary tasks (e.g. battle field patrolling), covert operations where displays may produce an unacceptable visual signature, and night time operations where visual displays disrupt night vision adaptation; and
  - b) Non-acoustic communication under the following conditions: high-noise environments where aural communication is difficult or would require excessively loud signals, low noise environments where audio signatures are unacceptable and/or may result in tactically relevant noises being missed.
- Non-visual and acoustic warning: used for control rooms that utilize lean manning where individuals are unable to continuously monitor an array of information, and for warning displays.

1.2.1 Air

The military aviation environment is both physically and cognitively demanding. We typically are not accustomed to navigating in three-dimensional space, and our orientation system did not develop under the extreme conditions of flight. Pilots are tasked with much more than simply flying the aircraft – they must perform navigation, make mission critical decisions regarding weapons deployment, conduct search and rescue operations, perform precision hovers in high threat environments, and maintain constant communication with tactical teams. These difficulties can be compounded by high levels of stress, fatigue, vibrations, sustained accelerations, hypoxia, thermal stress, and very poor visual conditions (e.g., night operations, white out, and brown out). Because aviation visual and auditory displays have been tasked to

provide enormous amounts of information, it is only natural that the military aviation community has begun to investigate the use of tactile displays to convey information to the pilot. One concept developed by the U.S. Air Force is the Spatial Orientation Retention Device (SORD). This device combines off-boresight visual symbology, 3-D audio cueing and a tactile vest. A conceptual drawing is displayed in Figure 1.2.

Figure 1.2: Spatial Orientation Retention Device (U.S. Air Force).

One of the most promising applications of tactile displays is for pilots performing precision hovers in poor visual environments, which may be in windy conditions. If a pilot drifts too far off the targeted position, tactors can be activated at various frequencies to indicate the direction and amplitude of the deviation. Similarly, a tactile display can be used for navigational purposes to inform a pilot when they have strayed too far off course. As described in more detail in Chapter 6, tactile cues are also highly effective for communicating the direction of potential threats. A pilot's attention can quickly be directed to the direction of a threat in a very intuitive fashion. A final application is for spatial orientation. Tactile information can be used to depict an artificial horizon, a down-pointer or up-pointer, or a command signal to convey a desired stick input.

1.2.2 Sea

The maritime environment is one of the harshest for human operations. It regularly subjects operators to arduous weather conditions and degraded visibility. To perform the required task with a suitable level of safety and aptitude requires operators to be provided with the appropriate tools for the job. This dictates that required information is available to the operator to ensure the correct level of situational awareness is attainable. It stands to reason that any system that enhances situational awareness will consequently improve performance and safety.

The contemporary demand for higher tempo operations, specifically in the military, coastguard and rescue domain, suggests that the demand for enhanced situational awareness has also grown. The ability for

surface, sub-surface, and airborne craft to operate at higher speeds means that the pilots and operators must be provided with the appropriate information at the right time so that optimal decisions can be made. This is particularly important when operating in poor weather conditions, close to land/obstacles, and at night.

The ability of computerised systems to provided operators with vast quantities of information has been found in all modes of transportation, but is particularly prevalent in the aviation sector. However, this phenomenon has been recently become evident in the marine operations where surface craft information systems must now display navigation, radar, boat systems and tactical information simultaneously. Unfortunately, the human operator possesses a finite ability to process this plethora of information. As a consequence, computerised displays can quickly overwhelm the operator's visual channel, which is further compounded with the fact that much of the data presented is of little use during certain periods of an operation. Therefore, the ability to provide information via non-visual senses can be an advantage for enhanced performance and safety.

A number of high speed craft trials have been successfully undertaken either in the maritime environment, or are such that they can be directly related to the marine environment [29][30]. These have primarily been for the provision of navigation/orientation cues, although other specific applications have been identified. Diver navigation using tactile cues has been successfully demonstrated by both US and UK researchers [31][32] by integrating the tactile display into computerised underwater navigation systems. An additional diving application for tactile displays is to provide enhanced situational awareness for mini-submarine (e.g., US Seal Delivery Vehicle (SDV) operations). This could include navigation, depth control and obstacle avoidance warning. Figure 1.3 shows a diver navigation system manufactured by Engineering Acoustics, Inc.

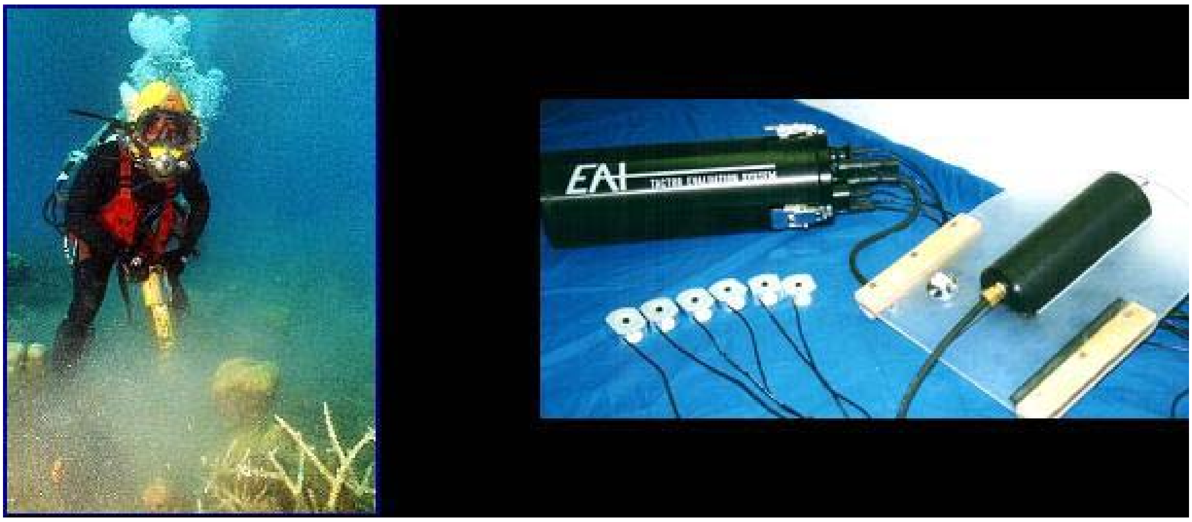

Figure 1.3: Diver Navigation System.

1.2.3 Land

Soldiers have specific and sometimes unique requirements for operation. Dismounted soldiers have a limited ability to carry power and equipment to support tactile displays and must have low noise and electrical signatures. They often operate in extremely demanding physical environments, and signals may be affected by the equipment they must wear and their close contact with the ground. Several concepts have been tested for dismounted soldiers both in daytime and in night operations. End users are particularly interested in the hands-free, eyes-free, and mind-free aspect of tactile displays. This allows

them to move with their weapon at the ready and with their eyes and attention focused on terrain and enemy threats. Applications include displaying waypoint navigation, terrain obstacles, off-limits areas, direction of threats, alerts on command decision making, threat location, target acquisition, support information for shooting performance, and tactile commands as substitutes for visual hand and arm signals. Studies have also been performed with tank operators using tactile displays as navigation aids as well as for target location. Soldiers in tanks or other ground moving vehicles do not have to deal with the same environmental stressors as dismounted soldiers, but often must operate in extreme noise and high vibration. Recently, several studies reported the potential of relatively simple tactile displays (usually consisting of no more than eight tactors in a belt around the waist) for land applications, including directional threat warning in armoured vehicles [33], dismounted soldier navigation [34], and communicating arm and hand signals [35]. Figure 1.4 displays a joint U.S. Army and TNO land navigation system.

Figure 1.4: Joint U.S. Army and TNO Tactile Array for Land Navigation.

1.2.4 Uninhabited Vehicles

Separating the operator from the vehicle means that the operator no longer receives direct sensory input from the remote environment, but only mediated information. This mediated information is usually restricted to (low quality) camera images [36][37][38]. This means that the remote operator is deprived of a range of sensory cues that are available to onboard operators, including somatosensation. According to the final report of the NATO-HFM Task Group on Unmanned Military Vehicles (UMVs), the loss of the rich supply of multisensory information often afforded to onboard operators is one of the challenges of advanced UMV operator interfaces. In the executive summary, the experts even state that *"....it could be said that the primary goal of the interface should be to reproduce the perceptual cues that are used by the operators in the real environment to perform the task"* [39].

The general belief is that tactile technology has a promising spin-off to uninhabited vehicles. There are two important arguments for this conviction. The first is that many of the crucial problems or bottlenecks

in the interfaces of inhabited military vehicles (e.g., sensory and cognitive overload) are also relevant for remote control interfaces. The second is that remote operators could benefit from the presentation of touch cues that are available onboard the vehicle but are absent in a remote control situation as stated above. The remote operator lacks valuable information, including vibration cues indicating platform and engine performance, pressure cues indicating forces acting on the platform, and environmental cues that can better be felt than seen, such as road condition in a ground vehicle and turbulence in an aerial vehicle. Van Erp [40] identified four application areas for remote control interfaces: navigation and vehicle control information, directional warning and attention allocation systems, situation awareness support systems, and reproduction of critical perceptual cues of the remote world.

1.2.5 Additional Application Areas

1.2.5.1 Telemanipulation

Beyond the previously described traditional applications of tactile display technology, emerging fields exist that expand their overall functionality and utility. Telemanipulation can be defined as the handling, operation, or utilisation of either concrete or virtual objects from a remote or otherwise detached location. For example, utilising gloves that provide tactile feedback, two individuals in different locations could jointly move or manipulate/modify virtual objects and "feel" the forces applied on the object by the other individual or object. Feedback including active touch or proprioceptive signals (e.g., force feedback, active exploration of an object) is typically referred to as haptics. Some potential applications of this technology include tactile/haptic feedback for medical applications (e.g., a surgeon performing surgery from a distant location), teaching applications (e.g., civil engineering students could "feel" the forces and stresses within a particular structure), and artistic applications (e.g., artists from a variety of regions might jointly form a virtual sculpture).

Additionally, telemanipulation could be used to control real objects while providing tactile feedback to the user. A potential application includes controlling a set of robotic arms in a variety of situations. One example involves disarming bombs and mines from a safe and distant location. Here, a robot (with mechanical arms) could be controlled by a human operator utilising gloves outfitted with haptic and tactile feedback. This would allow the human to feel the structure, wires, tools, etc. in his/her hands virtually to more easily manipulate the bomb components while maintaining safety. This expanding range of tactile/haptic feedback applications provides insight into the diversity of these displays.

1.2.5.2 Training, Simulation and Virtual Media, Gaming and Entertainment

Tactile displays are being explored with increasing frequency in the realms of simulation, training, and gaming. For simulated environments, tactile cues offer the potential of a greater sense of presence and improved task performance. Despite this potential, relatively little research has been done in this area. Li and colleagues [41] developed a haptic apparatus as a training aid for performing virtual catheterizations. Further, Gerling and Thomas [42] explored the use of a haptic feedback device for simulated breast examinations. They found that the use of haptic feedback resulted in improved training effectiveness, even though the sensations provided did not replicate those experienced during actual examinations. In the videogame industry, tactile feedback has become a relatively standard feature. It was first introduced in the home through force feedback steering wheels for PCs and add-on "rumble packs" for the Nintendo 64 and Sega Dreamcast controllers. Since then, vibration-based feedback has been incorporated into the controllers of several home video game consoles including Sony's Playstation 2 (see Figure 1.5), Nintendo's Gamecube and Wii, and Microsoft's X-Box and X-box 360.

Figure 1.5: Sony's Playstation 2 Controller with Vibration Feedback.

1.2.5.3 Therapeutic Applications

Applications under development outside the military environment are not within the scope of this report, although an influx of technology is possible. Therefore, we give a concise overview of therapeutic applications of tactile displays. Many applications have been developed for people with visual deficits. A successful device is the long cane used by the blind. In this case, tactile cueing can provide a natural correlation between the distal environment event and the proximal cue that is felt. Other devices include:

- A tactile vision-substitution system [43], designed to present optical patterns to the skin of the back.
- An optical to tactile converter called Optacon, developed to present patterns obtained from text registered by a camera directly to the fingertip [44]. It serves as a reading machine that provides vibrotactile spatial temporal patterns of alphabet letter shapes.
- The National Institute of Standards and Technology (NIST) has designed a refreshable tactile graphic display to allow the blind to receive information displayed on a computer screen and has developed a refreshable rotating wheel Braille display.

Similarly, numerous forms of prosthetic devices using the skin as an alternative sensing system have been developed for the deaf.

- In 1907, M. Du Pont proposed a tactile device that used direct electrical stimulation as an aid to communicate acoustic messages [45].
- Gault [46] developed a teletactor, a device that presented patterns to the fingers of the deaf.
- Tactile displays used as a hearing aid are typically based on the cochlea model of speech [47] where the acoustic signal from speech is sent through several bandpass filters that modulate the amplitudes of a corresponding array of tactors. Single and multipoint tactile aids designed to present analogues of the acoustic waveform in a one-dimensional array to the volar forearm were developed [48][49]. Both the linear electrocutaneous belt [50] and the two-dimensional multipoint electrotactile speech aid [51] displayed similar electrocutaneous patterns to the abdomen. Craig and Sherrick [52] developed dynamic arrays for tactile pattern presentation.
- Deaf students also learned to feel the vibrations of the pulsations of a balloon on the face and throat. This led to the development of vibrotactile aids (Tactaid VII Audiological Engineering Corp., Somerville, Massachusetts) that employ a linear array of tactors presenting vibration on the chest and the nape of the neck [53][54].

- The University of Sheffield is currently researching vibration elicited at the wrist to provide information from ambient sounds.
- A study by Sparks [55] used a 288 electrode tactile display to accurately provide auditory information on the abdomen. Each column referred to a band of frequencies and the subjects could identify segmental speech with 50 – 95% accuracy depending on the set of sounds used. In general, results from tactile hearing aid displays have been encouraging, but have not achieved great success or widespread use [45].

Another application to aid persons with disabilities is a sensory assistive device for those without sensation in their extremities.

- A study performed by Collins and Madey [56] used a special glove instrumented with strain gages on the fingertips. Each of the strain gages controlled the intensity of an electrode on the forehead. The results showed that subjects without sensation in their hand could distinguish rough surfaces from soft surfaces and could also detect edges and corners.
- Somatosensory displays can be used to provide proprioceptive feedback for spinal injury victims. A study performed by de Castro and Cliquet [57] introduced encoded tactile sensations relating artificially generated movements, provided by neuromuscular electrical stimulation systems, during walking and grasping activities. Paraplegics can use this sensorimotor integration to recognize artificial grasp force and to obtain spatial awareness of their legs during walking.
- Tupper & Gerhard [58] proposed the development of an electro-tactile stimulator that would provide positional and rate command feedback to motorized prosthetic arm users.
- Current applications of tactile displays include a vestibular prosthesis that provides information about body position and motion to patients with balance disorders in order to correct for body sway and to prevent falling [59][60].

1.3 HISTORICAL ASPECTS

In order to fully appreciate the myriad of tactile applications that have been described, it is useful to trace the historical aspects of tactile displays. The concept of presenting information via the sense of touch is not new. People have long ‘tapped each other on the shoulder’ to indicate their presence and the direction of their location. Also horse riders give instructions to the horse via tactile cues: the reigns pull on the horse’s head, and the feet push into the horse’s sides to give instructions to turn. Blind people have used tactile displays for many years (e.g., Braille and Moon alphabets). Also, military applications are many centuries old. In the late 1700s, Charles Barbier de la Serre, a French army captain, invented the basic technique of using raised dots and dashes for tactile reading and writing (Braille, Britannica Concise Encyclopedia). The original objective was to allow soldiers to compose and read messages/command orders silently at night without illumination. The raised dots represented words according to how they sounded rather than how they were spelled; this practice was known as sonography or “night writing”. Serre’s system was based on twelve dots. In 1824, Louis Braille further developed the method of touch reading and writing based upon conventional spelling using six dots; the Braille system as we know it today. The general concept and specific benefits of Braille remain relatively unchanged and unchallenged today, but the system has been complemented by an increase in speed and automation available through new electronics and computing power.

The attempt to employ tactile displays in aviation also has a lengthy history. As early as 1954, Ballard and Hessinger [61] proposed a vibro-mechanical tactile display system to indicate pitch and roll attitudes of the aircraft. The system consisted of four tactors mounted on the thumb. Two of the tactors provided pitch information and two provided roll information. The frequency of vibration indicated the magnitude of the deviation from the desired flight path. However, no results or further work on this system have been

reported in the open literature. Similarly, in 1961 Hirsch [62] proposed a tactile display for roll, pitch and yaw acceleration/velocity in aerospace vehicles using vibro-mechanical tactors on the thumb and forefinger. A kinesthetic and tactile aviation display consisting of an actuator mounted in the control stick that was capable of stimulating the hand (holding the control stick) was developed by Gilson and Fenton [21]. Movement of the actuator corresponded to the error (in degrees) from the desired angle of attack. Flight test results using a Cessna 172 suggested that the device allowed novice pilots to perform a tight turn about a point with less tracking error and contributed to decreased altitude and speed variations.

Morag [63] proposed a tactile display array inside the pilot's helmet to provide the spatial locations of targets or threats. He also suggested that the amplitude or frequency modulations of the tactile cues could be used to represent detailed information about the target such as the distance or urgency of the target. The part of the head that is stimulated represents the pilot's head-referenced angular direction of the target location. Gilliland and Schlegel [64] showed that the head was very sensitive to tactile stimulation. The localisation accuracy and response times varied inversely with the number of tactors available. For example, there was ninety-three percent accuracy with 6 tactor locations compared with 47% accuracy with 12 tactors. They further demonstrated that high workload (using dual memory and tracking task) did not interfere with the response time or localisation accuracy. However, performance during air combat simulation showed lower accuracy and longer response times. Zlotnik [65] proposed a matrix of electrocutaneous tactors embedded in a sleeve positioned on the forearm that would present airspeed, angle of attack, and altitude. However, no results or further work on this electrocutaneous device have been reported in the open literature.

In 1989, Rupert and colleagues renewed the idea that a tactile interface could be used as a "more natural" approach to convey position and motion perception during flight. This renewed interest resulted in many successful proofs-of-concept in rotary and fixed wing aircraft (see Chapter 6). Beneficial effects were shown over a range of circumstances including dynamic sustained acceleration, night operation, and situations of high mental workload. These successes and extensive research efforts have been responsible for bringing tactile displays to the precipice of introduction into operational cockpits. These efforts have extended to other military settings, including dismounted soldiers, remote control operators, vehicle and fast boat operators, and special forces.

1.4 SET UP OF THE REPORT

1.4.1 Definition of the Tactile Sense

There seem to be as many definitions of tactile displays as there are researchers working in the field. However, we use the following nomenclature throughout this report:

- Proprioception is related to all the senses that are included in the perception of oneself in space, including the sense of touch, the vestibular system and the haptic sense.
- Haptics / sense of touch / somatosensation all refer to the sensory systems related to both active and passive touch, including the mechanoreceptors in the skin and the receptors in muscles and joints.
- Tactile / cutaneous is related to stimuli that evoke a response in the mechanoreceptors in the skin only, thus excluding receptors in joints and muscles, and excluding noxious stimuli that evoke a pain sensation and temperature stimuli that evoke a sensation of cold or warmth.
- Vibrotactile is related to vibrating stimuli, thus excluding for example pressure stimuli.

Figure 1.6 depicts the relationship of the terms defined above.

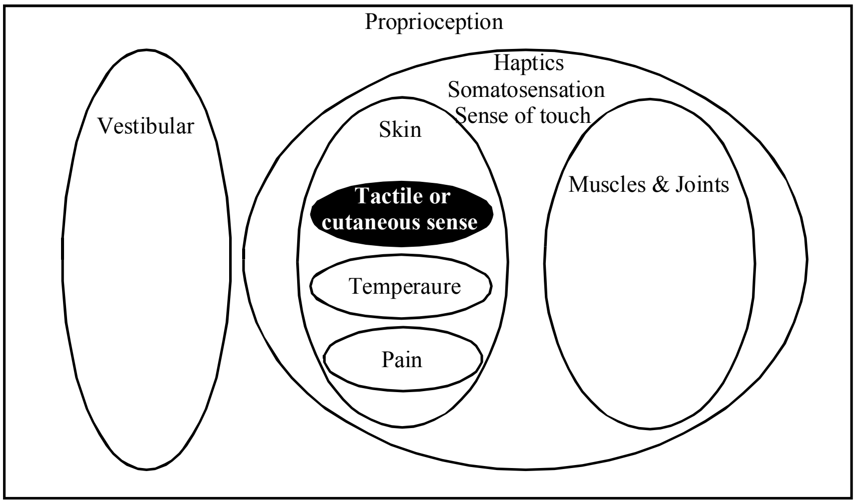

Figure 1.6: The Working Definitions of the Tactile Sense in Relation to Other Systems Used Throughout This Report.

1.4.2 The Remainder of This Report

The report is organised as follows. Chapter 2 provides a more detailed introduction of the sense of touch and its neurophysiological and psychophysical aspects. Chapter 3 presents detailed information on human factors issues and perceptual aspects relevant for military applications. Chapter 4 is focussed on (available) hardware and Chapter 5 details known hardware and system integration issues. Chapter 6 gives an overview of relevant applied research studies completed in this area, and Chapter 7 suggests future research topics.

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Chapter 2 – ANATOMICAL, NEUROPHYSIOLOGICAL AND PERCEPTUAL ISSUES OF TACTILE PERCEPTION

by

B. Cheung, J.B.F. van Erp and R.W. Cholewiak

In this chapter, we are concerned with what our touch receptors and the associated central nervous structures do. Our description begins with the anatomical and physiological characteristics of the touch receptors followed by a comprehensive psychophysical overview of touch sensation and perception. The conditions under which touch sensations and perception arise and the rules that govern them will also be described.

2.1 ANATOMICAL AND MORPHOLOGICAL CHARACTERISTICS OF TACTILE RECEPTORS

The anatomical and morphological characteristics of the touch receptors are well documented in numerous reviews [1][2, 3]. Only a brief summary is provided in this chapter. With respect to the sensation of touch, the innervations of the skin from various regions of the body are different from each other. There are some relatively elaborate structures associated with some of the nerve endings that respond to touch. There are also undifferentiated nerve endings that are involved in tactual response. The rapidly adapting mechanoreceptors present in the glabrous skin include Meissner's and Pacinian corpuscles. They are velocity-sensitive, discharging an impulse only during movement in the indentation of the skin. Meissner's corpuscles are encapsulated nerve endings that are located in the grooved projections of the skin surface formed by epidermal ridges. They can be found in abundance in the hand, the foot, the nipple, the lips and the tip of the tongue. Meissner's corpuscles are approximately 80 μm long, situated perpendicular to the skin surface. The receptor is connected to the skin surface by collagen fibres that enable the transmission of skin movement to the nerve endings in the corpuscle. They are sensitive to vibrotactile stimuli in the range of 10 – 100 Hz. Pacinian corpuscles are elliptical encapsulated endings, located in the deeper skin layers of both glabrous and hairy skin, which respond to rapid mechanical displacement of the skin. The Pacinian corpuscle is a layered structure, the mechanical characteristics of which limit the stimulus energy transmitted to the nerve endings to relatively high frequencies over the range of 40 – 600 Hz with optimal sensitivity around 250 Hz. There is a transient response to sustained mechanical displacement. The response is limited to the axonal membrane of the first node of Ranvier. Only one or two action potentials are seen when the generator potential is maintained at a steady level. Therefore, repetitive discharge does not occur in response to any steady component of generator potential that may be produced by temporal summation in response to repetitive stimulation. The receptor therefore produces impulses that follow the driving stimulus in the range of effective frequencies.

The slowly adapting mechanoreceptors include Merkel's disks and Ruffini's endings. They also discharge impulses in response to displacement of the skin; however, they can maintain a discharge of impulses in response to sustained deformation of the skin. These slowly adapting mechanoreceptors are sensitive to vibrotactile stimulation in the range of 0.4 – 400 Hz with varying characteristics and points of maximal sensitivity. Merkel's disks are found in the fingertips, the lips and mouth, with basket like terminations that surround hair follicles. Structures that look like Merkel's disks have also been found in epidermal domes that appear to be specialised receptor regions in the skin. The receptors are believed to respond to pressure applied perpendicularly to the skin at frequencies below 5 Hz. Ruffini's endings are situated in the dermis of both glabrous and hairy skin, deeper than Meissner's endings. It is believed that these receptors can provide continuous indication of the intensity of steady pressure or tension within the skin (e.g., lateral stretching).

Somatosensory information from mechanoreceptors ascends the central nervous system (CNS) by two main pathways: the dorsal-column medial-lemniscus pathway, and the anterolateral pathway. The dorsal column is made up of larger diameter axons from the dorsal root ganglion cells. It ascends ipsilaterally to the medulla and carries discriminative touch sensation, vibration sense, and information about joint and limb position. The anterolateral pathways originate from cells of the dorsal horn, cross at the spinal level, and ascend in the lateral columns, and carry information about pain, temperature sense, and crude touch. Also located in the lateral columns are the spinocerebellar tracts that are of importance in the cerebella control of movement. However, they do not contribute to the perception of somatic stimuli.

The lemniscal pathway consists of large myelinated axons, arising from A-beta sensory end organs (cutaneous mechanoreceptors that respond to pressure and vibration) located in the dermis of the skin. These axons course to the dorsal horn of the spinal cord, then branch into collaterals, which ascend in the posterior columns and terminate as climbing fibers on the dendrites of cells in layers III and V of the dorsal horn. Two ipsilateral tracts – the dorsal columns – form in the dorsal white matter of the spinal cord and ascend toward the cortex. Fibres from the lower extremities ascend in the gracile fasiculus, and fibres from the upper extremities ascend in the cuneate fasiculus. The dorsal columns terminate in the cuneate and gracile nuclei in the medulla. The axons synapse with neurons, decussate, and ascend in the medial lemniscus to the contralateral ventral posterior lateral nucleus (VPLN) of the thalamus. The VPLN also receive input from branches of the 5th cranial nerve, the trigeminal nerve, which transmits somatosensory information from the contralateral areas of the face. Neurons from the VPLN project to the primary and secondary somatosensory cortex, and to the parietal cortex, as well as sending collaterals to the reticular formation.

Phylogenetically, the anterolateral pathway is older; it conveys primarily pain and temperature signals from A-delta and unmyelinated Type-C end organs. The anterolateral pathway also conveys some tactile and joint information from A-beta fibres. Neurons that form the anterolateral pathway arise in layers I and II of the dorsal horn, decussate, and form three tracts on the anterolateral part of the white dorsal horn: the spinothalamic tract, the spinoreticular tract, and the spinotectal tract. The spinothalmic tract contains other A-delta fibers, similar to the dorsal-column of the dorsal-column medial-lemniscus pathway, and also projects to the VPLN of the thalamus. Both the anterolateral system and the dorsal column-medial lemniscal systems project to the posterior nuclear group of the thalamus. Many neurons in the posterior nuclear group receive converging projections from somesthetic, visual and auditory inputs and projects not to a specific cortical sensory area but widely, to many different regions of the cortex. As a result, the posterior nuclear group is thought to play a role in arousal. The somatosensory projection on the post central gyrus of the cortex is a horizontally distributed somatotopic representation of body geometry. In addition, there is a columnar organization of this region [4]. Neurons encountered in a microelectrode penetration perpendicular to the cortical surface are all of the same submodality and all have nearly identical peripheral receptive field locations.

2.2 PSYCHOPHYSICAL OVERVIEW OF TOUCH SENSATION

This report argues that there is a need for tactile displays, as well as demonstrates advantages when prototype display systems have been tested in the laboratory and field. But, to a large degree, there has not been a clear analysis of how to optimize the displays in any particular setting, nor for a particular body site (cref. Chapter 3). Before we discuss the possible ways to do this, a review of the manners in which the skin encodes information would be helpful. Furthermore, in these pages we hope to indicate the characteristics of the stimuli that should be attended to by applied researchers as they continue to develop and apply tactile displays.

The skin is a complex receptive organ, made more difficult to analyze because the receptor structures are buried deep in a multi-layered tissue matrix. The anatomical and physiological characteristics of skin have

been presented in the previous section. Suffice it to say that the structures that have been related to various types of tactile sensation (touch, vibration, temperature, pain) vary in their morphology, density, depth, and type as one moves from one point on the skin to another, and they are intermixed at any site. This kind of heterogeneous distribution leads to a number of implications for the development and application of tactile displays. Most importantly, one cannot depend on creating any particular unique sensation in a reproducible manner as one moves from body site to body site, or even from point to point, on the skin. A common demonstration of this “punctate” sensitivity is to lightly touch the point of a common pencil to various points on the back of the hand. The careful observer will notice that certain touches will feel “bright” or “cold.” In fact, the “experimenter/observer” has just activated his/her tactile cold receptors. In the same way that these are sparsely distributed over the hand, so are the structures apparently responsible for vibratory perception as one moves from region to region over the body’s surface. Weinstein [5] and Wilska [6] have demonstrated how several aspects of tactile sensitivity vary over the body’s surface. Although there are methodological complications with some of these data [7], there is little question that the variation in receptor density apparent over a region as compact as an individual finger [8] is a microcosmic representation of what exists over the surface of the whole body. Sensitivity is a function of receptor density, with the fingers, lips, and genitals having the greatest thermal and spatial acuity. Furthermore, the areas of cortex devoted to their representation are proportional to innervation density [9]. These facts lead us to several design principles that will be relevant to any real-world cutaneous display technology. First, stimulation at a site will activate, to one degree or another, all tactile receptors – not just one specific type. Second, the active driving element (the “contactor”) has to be of sufficient size to ensure activating at least some of these receptors, particularly on somewhat insensitive body sites like the abdomen or back. The following discussions of other characteristics of the physiological and perceptual characteristics of the skin will expand on these points and add additional principles to this list.

Verrillo and others have shown that the superior sensitivity of the skin to 250 Hz vibration only occurs for relatively large sizes of driver. Nevertheless, the Optacon, a 144-pin optical-to-tactile text converter used by the blind, was designed to vibrate at a high frequency with 0.25 mm pins [10], far below the minimum diameter to demonstrate the frequency sensitivity of the skin. In the years following, other tactors were designed (such as the Acoustical Engineering, Corp. Tactaid vibrators, or the Engineering Acoustics, Inc. C-2 drivers) to vibrate at these high frequencies. More and more data are accumulating to suggest that stimulus frequency might be irrelevant to the task at hand – some types of tactile pattern perception may not depend on this parameter. One example is the 25-year success of the Optacon. Given the poor spatial acuity of the Pacinian Corpuscles, the receptors intended to be driven by the stimulus frequency of the device [11], persons could, in practice, read vibrotactile text at over 100 words per minute (e.g., [12]). More recent data have shown that stimulus frequency may in fact not play a role in vibrotactile localization. Studies specifically comparing different tactor types have shown similar results (e.g., [13]) in which localization was not only independent of stimulus frequency over the range of 40 – 250 Hz, but over modes of stimulation (perpendicular indentation of the skin versus rotatory shear from pager motors). A reasonable question that can, therefore, be raised, is whether the findings of basic research have much to do with applied issues. Theory, based on carefully-controlled laboratory studies, argue one way, but when reality rears its ugly head, we find that, like vision and audition, touch seems to do better with the stimuli presented to the skin than one might expect knowing the physical parameters of the signal. Regardless of whether it is a pager motor, pneumatic tactor, high-frequency vibrator, or a mosquito, our ability to localize stimuli on the body seems to be better than we might expect. As in much of perception, the organism tries to extract the relevant parameters from the stimulus for the task.

If stimulus frequency (and the underlying primary receptor population) does not play a role, what factors can be assumed to affect the operation of a tactile display? There are several that should be taken into account. Of these, we will briefly discuss spatial resolution, adaptation and habituation, and age.

There is a considerable interest in creating high-density arrays of tactile stimulators. It is clear, however, from the data on the spatial resolution for touch, that the skin is not uniformly acute over its surface [14]

[5]. These data, however, have been collected only for durative pressure stimuli, not vibration, the dominant mode of tactile stimulation in display devices. In analyses of tactile resolution for vibratory stimulation, the required separation for accurate identification of individual sites (as might be required for targeting) is somewhat greater than one might expect. This is the case because vibration travels both over the surface and deep in the tissues that make up the skin (e.g., [15]). About three vibrating sites can be accurately localized (without error) on the forearm [16] while that number increases to seven evenly distributed loci on a belt around the abdomen [13]. These numbers were independent of stimulus frequency over the range of 40 to 250 Hz, as well as mode of stimulation. Even height around the waist did not affect this resolution: localization tactors around the waist 25 mm above the navel was identical to 100 mm above the navel. This was somewhat remarkable because of the extreme differences at the two levels in the underlying tissue – including ribs, muscle, and gut. Although we are unaware of comparable data in the literature regarding localization as a function of height on the trunk, successful displays involving 3 to 5 vertical rows of vibrators have been tested successfully to provide directional cues to operators [17][18][19][20], supporting the estimate from the information calculations. However, this limitation is only valid for identification tasks, which are fundamentally different from discrimination tasks. Work from TNO in the Netherlands suggests that the number of tactors around the waist for discrimination tasks can be much larger. Based on experiments measuring the spatial resolution on the torso, it was estimated that the number of stimulus sites that can be discriminated around the torso is on the order of 24 [21]. In direction discrimination experiments, the standard deviations found for sites around the torso are typically on the order of 10° [22], indicating that up to 36 tactors around the waist may be discriminable. Also, displays using much more than 3 – 8 tactors around the waist have been successfully tested (e.g., Van Erp et al. [23] used 24 columns around the torso).

The psychophysical studies discussed so far did not employ a very powerful tactile cue that has not yet been discussed: movement (the applied studies did, however). Extensive studies, particularly by Essick, have shown that even with very dense arrays, including far more loci than could be uniquely identified, judgments of the direction of apparent movement produced by sequential activation of tactors can be virtually perfect in many conditions. He studied a number of body sites with several types of stimuli, including moving brushes or probes as well as virtual motion on dense arrays of tactors, on the fingers, face, arm, and other loci, with similar results [24][25]. Testing seven sequentially activated sites on the forearm, subjects were essentially perfect in identifying the direction of apparent movement, regardless of spatial velocity [26]. These were the same sites and tactors which were used to test absolute localization, as described earlier. It was found that information about the loci of only 3 of the 7 was transmitted. When similar “moving” stimuli were generated over 12 sites surrounding the waist, the same sites described earlier in which only information about 6 were transmitted, direction of apparent movement was again perfectly identified [13, 16]. The principle to emerge from these results is that if possible, one should employ changes in the location of active tactors to encode the information to be transmitted.

Another less obvious advantage of moving stimuli is that they will reduce the possibility of another complication in tactile pattern generation: adaptation. Later in this section we will distinguish adaptation from the similar perceptual phenomenon, habituation. Adaptation may be generally defined as a reduction in sensitivity resulting from a continuous unchanging stimulus. Examples in vision, taste, and olfaction abound in everyday life. For example, our awareness of a smell in a room, whether pleasant or not, will often reduce or even disappear, only to return if we leave then return, confirming that it is not the stimulus but rather our response to it that has changed. With regard to touch, one of the reasons that we become unaware of the pressure of our clothes on our bodies is because of the mechanism of adaptation. But move an arm, and the changes at the edges of a sleeve or shoulder are immediately perceived. Adaptation occurs to durative suprathreshold stimuli and can disable or desensitize a given tactile channel [27], [28]). Typically, this occurs if vibratory stimuli last more than about 200 ms. If adaptation occurs, it is possible to still stimulate the skin by appealing to other channels by appropriate selection of stimulus frequency and amplitude. This is possible because adaptation to a frequency appealing to one channel (e.g., 250 Hz) has no effect on threshold at a frequency that appeals to another channel (e.g., 20 Hz).

In fact, adaptation with single contactors has been used to separate out the physiological channels described in the Bolanowski model (e.g., [29]) because of the absence of cross-adaptation. By these and other methods, the channels have been shown to be independent ([30][1]).

Habituation, on the other hand, occurs with repetitive stimuli but does not result in a change in the sensitivity of the sensory system. Rather, this appears to be an effect of attention. The everyday example of habituation occurs when we lose awareness of a ticking clock. If attention is drawn to the clock, we immediately become aware of the sound, so this indicates neither stimulus failure nor receptor desensitization. Should the clock skip a tick or change beats slightly, "dishabituation" occurs, and awareness returns. One way to address habituation and adaptation in an applied situation is to avoid long periods of stimulation. In flight, for example, this can be achieved by establishing null zone conditions in which tactor activation does not occur in stable situations such as straight and level flight or stationary hover. This prevents the operator from desensitizing to a continuous stimulus (adaptation) or to one that is constantly repeating (habituation). A pattern having a well-chosen stimulation duty cycle (e.g., off cycle is three times as long as on cycle) may prevent adaptation altogether [31, 32], although habituation may still be an issue.

Finally, if a tactile display is to be used by young and older persons, one might have to consider the changes in tactile sensitivity and acuity that occur with aging. A number of survey articles have discussed these changes in detail (e.g., [14][33][34]). Even if the intended population is only older, it is likely that the data that contributed to the development of the tactile display were collected on a younger population – usually college-age students. This has been a particular problem with devices intended to help in cases of sensory handicap. The population that is most commonly afflicted with these is older than 60 years – the population showing deficits in spatial acuity, vibrotactile sensitivity, and temporal resolution (e.g. [16] [35][33][14][34]). However, it has also been reported that in an operational setting, older observers (60 to 70 years) performed as well as the ones between 40 – 50 years old in detection threshold and spatial and temporal resolution [36][37].

2.3 AVAILABLE PSYCHOPHYSICAL DATA RELATED SPECIFICALLY TO THE CONDITIONS UNDER WHICH TOUCH SENSATION AND PERCEPTION ARISE

2.3.1 Difference Threshold

The difference threshold is the amount of indentation that is related to the minimal required change in amplitude to be detected. Craig [38] reported that the Weber fraction ($\Delta I/I = K$, where I is the stimulus intensity and K is the constant) for tapping depends on the stimulus intensity. Higher Weber fractions result from low intensities (0.35 at 15 dB) and lower Weber fraction for higher intensities (0.25 for 25 dB and higher). For bursts, the Weber fractions were 0.20 and constant over the range of stimulus intensities (15 – 35 dB). In addition, background vibration [38], and adaptation [39] also have an effect on the difference threshold.

2.3.1.1 Absolute Detection Threshold

Sherrick and Cholewiak [40] indicated that the absolute threshold for vibrotactile stimuli for the trunk is 4 microns at 200 Hz. A more extensive study by Wilska [6], who measured thresholds for 200 Hz vibration over the body, suggested a threshold of 4 microns in the lower part, 2 microns in the upper part, and 4 microns in the dorsal side of the torso. Verrillo [41, 42] measured thresholds for vibrotactile stimuli on the glabrous skin as a function of frequency, location and several contactor properties. The threshold as a function of frequency was U-shaped with a maximum sensitivity in the region of 250 Hz. However, this value is only valid for relatively large contactor areas. Verrillo [43] also determined absolute

thresholds as a function of frequency on the hairy skin of the volar forearm. There were two marked differences with the results found with glabrous skin. First, thresholds on hairy skin were higher than those on glabrous skin. Second, the maximum sensitivity shifted from 250 Hz for glabrous skin to 220 Hz for hairy skin. The thresholds for force as measured by Weinstein [5] are in the order of 60 – 80 milligrams for the torso. Other factors that have an effect on the absolute threshold are the contactor lay-out [35], the presence of a rigid surround, how deep the contactor is pressed into the skin [41, 42], waveform, and temperature [44].

2.3.1.2 Subjective Magnitude

The intensity of a stimulus is often indicated with reference to the absolute threshold of the stimulus (dB SL). However, stimuli with the same objective intensity level are not necessarily perceived to be equal in subjective intensity, and doubling the objective intensity or amount or energy does not necessarily result in a doubled subjective intensity. Verrillo, Fraioli and Smith [45] found that the subjective magnitude as a function of objective magnitude is a power function with an exponent around 1 (i.e., close to linear). Other factors that have an effect are the stimulus duration [46], the number of successive bursts [47], the presence of static surround [48], the frequency and intensity of a preceding stimulus [47], and the number of simultaneous vibrators [49]. As a coding parameter, (subjective) intensity seems less appropriate, and not more than four different levels should be used between the detection threshold and the comfort/pain threshold [38].

2.3.1.3 Spatial Summation

Sherrick and Cholewiak [40] concluded that the sense of touch exhibits spatial summation (change in threshold as a function of the area of stimulation), but that it is small and probably a central and not a peripheral process. Makoes et al. [50] investigated spatial summation under different conditions. Their results suggested that spatial summation exists for all types of skin under high frequencies. However, for low frequencies, spatial summation was present on the hairy skin of the forearm but not on the glabrous skin of the hand. Other factors that have an effect are skin indentation, pressure and force [51], intensity level [52], and the number of loci [53].

2.3.1.4 Psychophysics of Localization

Issues relevant to the perception of stimulus location are: how well one can determine the location of a stimulus (absolute localisation), how well can one distinguish different locations from each other (relative localisation or the spatial resolution of the skin), and how can spatially separated stimuli influence each other (spatial masking).

2.3.1.5 Spatial Acuity of the Skin

Spatial acuity has been investigated by several methods, including two-point discrimination, gap detection, grating resolution, and letter recognition [54]. It should be noted that most studies used pressure and not vibrotactile stimuli to measure spatial acuity [16] and that most studies investigated the fingertips only. Because vibratory stimuli act upon different sensory receptors and result in both longitudinal and shear waves that may degrade spatial resolution (see [55] for wave propagation models for the skin), results using pressure stimuli may not be generalised. A classic study by Weinstein [5], who measured thresholds of two-point discrimination and tactile point localization on several body loci using pressure stimuli, demonstrated that there is an enormous difference between different body loci (see also [14]). Lowest thresholds were found for the fingertips, about 2 mm. Thresholds for the trunk were much larger, up to 4 cm. The sensitivity decreased from distal to proximal regions (see also Vierodt's law of mobility; [56]), and acuity correlated with the relative size of cortical areas subserving a body part [9]. Other factors that have an effect on spatial resolution are temperature of the objects that are touched [57] and of the skin

itself [58]. The frequency range of the vibration appeared to have little effect on spatial localization, and the apparent points were more difficult to localize than physical points [59]. Regarding hyperacuity in tactile sensation, it has been shown that the thresholds for frictionless shifts in the position of a point stimulus on the torso [60] were 10 – 30 times smaller than the resolution reported by Weinstein [5]. In addition, judgments of the direction of apparent motion induced by dense arrays of tactors are much better than predicted on the basis of local spatial resolution [24, 25]. Recently, important work on stimulus identification and discrimination was published. Cholewiak, Brill and Schwab [13] concluded that the number of unique stimulus sites that can be identified around the torso is about seven. Van Erp [21] found that the spatial resolution around the torso for vibrotactile stimuli is relatively uniform over the torso and in the order of 3 cm.

2.3.1.6 Psychophysics of Temporal Events

The role of time in cutaneous perception includes temporal resolution (acuity) of the skin, temporal masking, summation effects and also adaptation. Temporal acuity is the minimal difference in the time domain required to distinguish two stimuli including temporal order (which came first), duration, and gap detection. Several methods have been used to measure temporal acuity, such as temporal numerosity [61]. Unimodal threshold studies have shown that the temporal resolution of the skin lies between those of hearing and vision [62]. This relationship extends to discrimination of duration [63], synchronization of finger taps [64], and adjusting empty intervals to equal pulse duration. Hirsh and Sherrick [65] investigated the perception of temporal order (i.e., the ability to judge which of two successive tactile events came first), where the observers had to judge the temporal order as well as which pattern was presented first. The results demonstrated that an increase in temporal separation also increased the percentage of correct distinctions between the stimuli. With a 20 ms separation, this percentage was 75%. This 20 ms threshold is larger than that obtained for successiveness measurement only. Gescheider [66] measured the perception of successiveness as the ability of observers to distinguish between successive and simultaneous events. He showed that two stimuli of 1 ms must be separated by 5.5 ms to be perceived as two stimuli at a single locus on the fingertip. Petrosino and Fucci [67] measured thresholds of successiveness as the ability to accurately count a series of events presented within a temporal epoch and found that thresholds increased with age and locus that ranged from 13 to 30 ms. Craig and Baihua [68] measured temporal order judgements for stimuli presented to a single fingerpad (same site), to two fingers on the same hand (ipsilateral), or to two fingers on opposite hands (bilateral). Thresholds were 12 ms for the same-site condition, 65 ms for the bilateral condition and 125 ms for the ipsilateral condition. In a controlled experiment, subjects judged which of two locations received a pattern first when the same pattern was delivered to both locations. Thresholds for the bilateral and ipsilateral condition were similar to those obtained by Hirsh and Sherrick [65], although they used a 1 ms-pulse instead of a vibration stimulus of 26 ms.

2.3.1.7 Short Burst Duration

In general, stimuli with short burst durations (BDs smaller than 30 ms) are hypothesised to be processed differently by the nervous system [69 – 71], although direct psychophysical data are not available. For example, Hill and Bliss [72] suggest that for small BDs, the sequence of the presentation but not the content is lost when 24 inter-joined regions of the fingers were stimulated. Kirman [71] suggested that a larger stimulus onset asynchrony (SOA) is required for stimuli with smaller BD to be felt as successive instead of simultaneous stimulation. In order to perceive smooth apparent motion, a steeply rising SOA is required for BD values below 30 ms.

2.3.1.8 Temporal Difference Thresholds

Very few studies have investigated the difference thresholds in the Weber fractions for temporal intervals. The Weber fractions ranged from 0.10 [73][74][63] to 0.25 [75] for stimulus durations shorter than 1 s.

Van Erp and Werkhoven [76] found that the Weber law holds over the range of empty intervals between 100 – 800 ms, with a Weber fraction of 0.20.

2.3.1.9 Temporal Summation

The relationship that exists between the duration of a stimulus and the threshold required for detection is known as temporal summation. Verrillo [77] found effects of summation to require a minimal area of stimulation. Summation effects were found up to durations of 1000 ms. For taps, temporal summation is exponential for the range 1 – 10 ms and constant for 10 – 100 ms.

2.3.1.10 Adaptation

Adaptation corresponds to a change in the percept of a stimulus after prolonged stimulation. The absolute threshold increases and the magnitude of sensation decreases with increasing adaptation. The time constant of the adaptation process is approximately 2 min [78]. The effects can be found up to 25 min, after which the change in threshold is about 17 dB and the change in sensation about 6.5 dB. Recovery time is approximately half the duration of the adaptation time [31, 32]. Adaptation does not occur across frequency bands [47, 78, 79]. O'Mara et al. [80] reported that extended exposure to a vibratory stimulus produced substantial changes in the responsiveness of subcortical cells but not in the peripheral afferents, suggesting that vibrotactile adaptation is largely a central process.

2.3.1.11 Frequency of Stimuli

As with the other parameters, one can also manipulate the frequency of stimulation. However, when the frequency varies, care must be taken to maintain constant subjective intensity since subjective magnitude of vibrotactile stimuli is frequency dependent. Goff [81] found that the Weber fraction of frequency increased with increasing frequency and for stimuli with a lower intensity, and ranged between 0.18 and 0.55. Cohen and Kirman [82] demonstrated that thresholds increased for stimuli with a duration of 30 ms. The Weber fractions were reported to be on the order of 0.20 – 0.25 for frequencies between 20 and 300 Hz [83]. Goff recommends that frequency should not be used as an information parameter in tactile communication systems at high frequencies.

2.3.1.12 Spatiotemporal Perception

The perceptions of apparent motion, apparent position, and relative location of two or more consecutively presented stimuli (point localisation) when using vibrotactile stimuli are based on the processing mechanisms of spatiotemporal patterns. This implies that there is a potentially powerful mechanism that is able to integrate place and time. For example, judgments of the direction of apparent motion can be more accurate than spatial resolution performance [24, 25], but may also result in masking effects. Spatiotemporal processing in the primate and human brain is presumably based primarily on location, lateral inhibition and facilitation. Through these processes, neurons sensitive to specific spatiotemporal patterns were developed. This assumption is logical because representations in the somatosensory cortex and other areas involved in the processing of somatosensory stimuli are location based (also called somatotopic). Spatial relations are carefully preserved in the neuronal pathways and in the representations in the cortex.

2.3.1.13 Sensory Saltation

Saltation [84 – 86] refers to the area where mislocalisation occurs for two successive and spatially separated stimuli. They can be found over the whole body, but never cross the body midline. Their size and form are related to those of the cortical receptive field (RF). The process exists for strict timing parameters, of which the inter-stimulus interval (ISI) has a major influence. BD must be in the order of

5 ms. The vividness and strength of the saltatory effect is supported by psychophysical data from a study done by Cholewiak and Collins [26]. They investigated the perception of different line qualities (e.g., length, smoothness) under veridical and saltatory presentation modes as functions of the timing parameters. They concluded that there were no differences between the two modes.

2.3.1.14 The Cutaneous Rabbit

The cutaneous rabbit is the name given to a spatiotemporal perceptual illusion that made the researchers conjure up a vision of a tiny rabbit hopping over their body [87]. The rabbit illusion also occurs under strict temporal parameters. Again the BD must be very short (i.e., a tap in the order of 2 ms). This illusion is based on a series of these taps, delivered to two separate locations, with multiple taps at the first location. When the timing between the taps is correct, the observer perceives numerous individual taps spaced between these two locations. This sensation resembles both saltation and apparent motion, except for the fact that individual taps are perceived instead of continuous motion. For ISIs larger than 200 ms, the effect is absent. For ISIs between 200 and 100 ms, the displacement starts, with the taps more or less evenly spaced at 100 ms ISI. The illusion is optimal for ISIs between 40 and 60 ms for a five-tap rabbit. The number of taps becomes illusory for ISIs below 40 ms. The importance of the timing parameter is confirmed by the fact that gaps in the stream seriously degrade the illusion. Besides the ISI, the number of taps is also important but not the distance: 2 taps are sufficient, 4 – 6 is optimal, 18 taps are too much. The “rabbit” sensation can cross the body midline only if one of the locations is on the body midline. The illusion is very strong when both locations are within the same dermatome, but very weak or absent between dermatomes [87].

2.3.1.15 Apparent Motion

Apparent motion is a perceptual illusion in which two or more non-moving stimuli activated in a specific spatiotemporal pattern evoke a percept of continuous motion. The percept is not always stable. Although mentioned in the early psychophysical literature (e.g., [88]), it was not until the 1960s that researchers were able to evoke a reproducible effect [69, 70, 89]. Sherrick reported that apparent movement could be induced by successive bursts of vibration but not by pressure stimuli, which yield unreliable judgements of movement. It has been shown that the significant variable for the appearance of ‘good’ movement is the interval between onsets of stimuli, or the stimulus onset asynchrony (SOA). Sherrick investigated which variables determined the optimal SOA for good movement. The following variables had no effect on the quality of movement or the optimal SOA: vibration frequency (60 – 250 Hz), body locus (forearm, back, stomach, hand), subjective magnitude (6 – 30 dB SL, see also [90]), direction of motion (proximal-distal or vice versa) and magnitude imbalance (when one stimulus had twice the intensity of the other). Burst Duration (BD) was crucial for good apparent movement: the optimal SOA varied linearly with BD in the range between 25 and 400 ms (with SOA about 0.70 of the BD, and an offset of 60 msec). Kirman [71] used a subjective rating method to measure the quality of apparent movement. The degree of apparent movement varied as a function of SOA: the function first increased and then decreased. Both the optimal SOA and the impressiveness of apparent movement increased with a BD above 20 ms. Apparent motion is thus an illusion that is mainly related to timing parameters (and the number of stimulus sites, [91]).

When the required SOA for apparent motion is plotted as function of BD, the typical pattern shows a decreasing SOA for BD values until a bottom value around 30 ms (which is equivalent to a decreasing ISI for larger BDs as found in [92]) is reached. For BDs above 30 ms, the required SOA increases again [71, 92]. This typical pattern is absent in studies that did not use BDs near or below 30 ms. What is remarkable about the dip is that it is located near the threshold for temporal order and the critical BD value below which stimuli are hypothesised to be processed differently.

2.3.1.16 Pattern Recognition

Pattern recognition (i.e., the identification and discrimination of patterns, see also [93]) as a function of timing parameters has not extensively been studied. Cholewiak and Craig [94] report that their data is more accurately described by SOA than ISI.

2.3.1.17 Masking

Masking is a change in the percept of a stimulus (target) when a second stimulus (masker) is close in time and/or space. The masker may (negatively) affect several aspects of the target, including the absolute threshold, the difference threshold (e.g., [95]), and the perceived location. Furthermore, observers may respond to the masking stimulus as though it was the target (also called response competition, which assumes that both target and non-target interfere at a later state of processing [96, 97]). Temporal masking occurs when two patterns occupy the same location at different times. In general, the interference between the patterns decreases when the temporal separation between the onsets of the two patterns increases. The masking pattern can be presented prior to the pattern to be identified (forward masking) or subsequently to the target pattern (backward masking). Both types do not always result in the same amount of masking [98]. At brief SOAs (< 100 ms) they found more backward than forward masking. However, when the SOA was relatively long (> 200 ms) backward masking became negligible whereas forward masking remained visible for SOAs up to 1200 ms. This is consistent with the results reported by Bliss et al. (1966). However, Gescheider, Bolanowski and Verrillo [99] did not find any differences and Weisenberger [100] reported more forward masking than backward masking for relatively short ISIs. The difference between the above mentioned studies might be due to the difference between signal detection [99, 100] and pattern recognition [98, 101]. It is possible that different processes are involved in detecting simple vibrotactile signals and in recognising complex patterns of stimulation. Other factors that may affect the amount of temporal masking are the type of masking stimuli [102] and the frequency of the stimuli (no cross-channel masking [103]). Spatial masking occurs when two stimuli occupy two locations but at different (possibly overlapping) times. Sherrick [104] measured the detection threshold of a pulse masked by a second pulse as a function of the ISI and the spatial distance. He demonstrated that the amount of masking decreased when the spatial separation between the two stimuli increased. He also found that contralaterally placed maskers showed masking effects, which indicates that the interaction between the pulses is not solely a peripheral process but also requires some degree of central involvement. Verrillo and Gescheider [103] found masking (increased detection thresholds) predominantly for high frequency stimuli. A very specific situation occurs when a target is masked by another stimulus that is presented at the same location and at the same time. Gescheider, et al. [105] measured this by presenting a specific target (an amplitude change) in a continuous white noise vibration. The thresholds increased with increasing masking intensity. Finally, masking can occur when target and masker overlap neither in time nor in space (although they are in close proximity both spatially and temporally). Weisenberger and Craig [106] instructed subjects to identify vibrotactile patterns presented to their left index fingertip in the presence of spatially adjacent masking stimuli. Forward and backward masking decreased with increasing SOA (although actually ISI is a better term to indicate the amount of overlap). Maximum interference in pattern recognition was found to occur at an SOA of about 50 ms.

2.3.1.18 Models for Spatiotemporal Processing

In general, the psychophysical theories do not agree on the specific mechanisms underlying spatiotemporal integration or masking phenomena. Some theories on masking are discussed briefly. Bliss et al. [101] described masking with a model consisting of three intervals:

1) A read-in interval of 50 to 100 ms in which stimuli occurring in the interval are superimposed;
2) A period of 75 to 200 ms in which a second stimulus may cancel or replace the first stimulus because both stimuli occur in the same temporal epoch; and
3) An interval in which the mutual interference between the two stimuli is reduced.

Craig [102] and Craig and Evans [98] suggested that temporal masking obtained with vibrotactile patterns occurs because of two processes: interruption and integration. Interruption arises when the features of a target are distorted or confused with features of a masker. It is responsible for producing greater amounts of backward masking than forward masking. Temporal integration operates in both backward and forward masking paradigms. Two patterns that are presented in close temporal and spatial proximity are integrated into a composite form in which the target pattern is obscured.

Craig and Evans [98] argued that the presentation of a vibrotactile pattern yields an internal representation that persists following the cessation of a stimulus for a certain amount of time. They demonstrated that forward masking occurred for SOAs up to 1200 ms. The information contained within the tactile sensory store decays rapidly at first (until SOA = 100 ms) and decays at a slower rate (until SOA = 1200 ms). Backward masking is strong at SOAs < 100 ms since information presented to the same place of the skin is integrated over a temporal window of approximately 100 ms. The reason that at relatively long SOAs there is more forward masking than backward masking is that the representation of a pattern persists for about 1200 ms.

Gescheider, Bolanowski and Verrillo [99] mentioned that according to Kirman [107], forward masking may be primarily a peripheral interaction maximally evident when peripheral interaction between target and masker occurs, while backward masking has a strong central component. However, Craig and Evans [98] discussed that the persistence of features of vibrotactile patterns after stimulation, which explains forward masking at long SOAs, is probably not a peripheral process. Gescheider et al. [105], who found that the effect of a masking stimulus on the vibrotactile threshold was independent of frequency, concluded that either the neural processes responsible for vibrotactile masking must be the same for each vibrotactile channel or the process operates at a level in the central nervous system that integrates information across the psychophysical channels. However, the first conclusion seems to be more likely, since Verrillo and Gescheider [103] found that masking did not occur between these channels.

2.4 CONCLUDING REMARKS

This chapter describes the anatomical and psychophysical aspects of the sense of touch. It shows that the sense of touch is very complex, consisting of many specialized receptors and cortical projections. Although the body of psychophysical data is much smaller than for the visual and auditory senses, the information required to design vibrotactile displays is available. Basic information on factors such as the spatial and the temporal resolution is available and presented here. However, data on other stimuli than pressure or vibration (for instance electrocutaneous signals) are still sparse. With respect to vibration stimuli, it can be concluded that location and timing are the two most important stimulus parameters, also strongly interacting with each other. This can for example result in apparent motion and spatial masking. Psychophysical data are especially relevant to the human factors of tactile displays, which will be discussed in Chapter 3.

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Chapter 3 – HUMAN FACTORS ISSUES OF TACTILE DISPLAYS FOR MILITARY ENVIRONMENTS

by

B.P. Self, J.B.F. van Erp, L. Eriksson and L.R. Elliott

The overall goal of this chapter is to give the reader insights into the human factors issues related to the use of tactile displays. Torso-mounted displays, which are particularly suited for direction and orientation cues, are emphasized. First, perceptual issues relevant to tactile stimulation are discussed. These include issues regarding spatial acuity and absolute localization of tactile cues on the torso, such as internal reference points, anchor points, and spatial accuracy. In addition, tactile illusions, burst durations, and temporal effects are discussed in relation to tactile torso display design. A second section focuses on issues related to coding principles; that is, how best to develop tactile patterns to be intuitively understood within a specific operational context. Cognitive issues are then addressed, such as how tactile stimulation can either alleviate or exacerbate attention tunneling, and the extent to which multiple tactile patterns can be used effectively. Cognitive processes related to tactile cueing are described, followed by issues related to multisensory integration and multifunction displays. Finally, issues related to user acceptance are discussed.

3.1 PERCEPTUAL ISSUES

Chapter 2 discussed the sense of touch and related perceptual issues at a general level. Since it is expected that tactile displays in military environments will often use vibrotactile stimuli applied to the torso (see Figure 3.1 for an example; see also Chapters 4 and 6), we will present more detailed perceptual data below. The relevant perceptual issues include the spatial acuity of the torso for vibrotactile stimuli, the ability to localize stimuli on the torso and the perception of external directions based on a localized vibration on the torso.

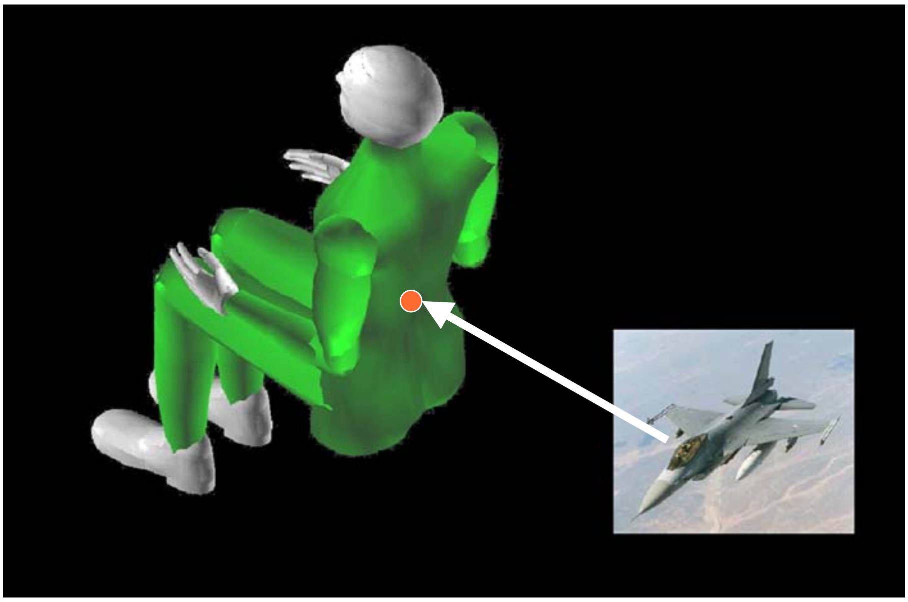

Figure 3.1: Example of the Use of a Tactile Display in a Military Environment. The localized vibration on the pilot's torso presents the direction of an aircraft.

In experiments investigating the spatial acuity of the torso, Van Erp [1] found an evenly distributed resolution of 3 – 4 cm, except for the horizontal direction near the body midline where the resolution was 1 – 2 cm. A possible explanation for this phenomenon (which was called the midline effect) is that the way vibrotactile stimuli on the torso midline are processed makes the midline a so-called anchorpoint. Stimuli on the body midline are processed in both the ipsilateral and the contralateral hemisphere (cref. Chapter 2). Previous studies have shown that anatomical anchorpoints improve performance in vibrotactile localisation tasks [2].

Spatial acuity is concerned with the relative localisation of two stimuli. However, for a tactile display that maps an external event (e.g., the direction of an aircraft) on a specific location on the torso, absolute localisation is also relevant. Van Erp found that observers are able to localise a vibratory stimulus close to its veridical location. The pattern of responses indicates that stimulus locations on the torso may be coded in polar co-ordinates with the body midaxis as the origin. When the true, or veridical, and observed stimulus location do not coalesce, the difference is in distance but not in angle (shifts up to several centimetres occur, which actually means that observers could have localised the stimulus below or above the skin surface). Interestingly, a shift along the radius has no effect on the perceived direction of the stimulus. The results indicate that angles are the perceptual invariant for torso stimuli.

The critical perceptual issue for tactile displays now becomes whether observers are able to externalize a localized vibration on the torso to a direction in the external world, and what the accuracy (and bias) is in this direction perception. Van Erp [3] investigated direction perception with a horizontal belt with 15 tactors around the waist. Inspection of the response patterns revealed that observers did not use the body mid-axis as the origin for the observed direction, but used two spatially separated internal reference points, one for each body half. The results show that the accuracy is dependent on the location on the torso: variability is lower on and near the midsagittal plane (4° for the direction straight ahead) than on the sides of the torso (10 – 14°), probably due to the fact that the midline locations act as anchorpoints. There was also a bias in the perceived direction. This bias is toward the midsagittal plane, that is, perceived directions are toward straight forward for tactors on the frontal side, and toward straight backward for tactors on the dorsal side when compared to their veridical directions. The bias is close to 0° for the four cardinal directions and increases up to 10° for the directions in between. Although this may be acceptable for many applications (for example, the 12 hours of the clock used in military environments to indicate directions have a 30° resolution), some applications may require greater resolution. Such situations may require individual calibration of the mapping of perceived directions on skin locations, that is, constructing a torso-related transfer function (TRTF). The TRTF would map each perceived direction to a unique location on the torso. Although individually derived TRTFs will optimally reduce the difference between perceived and actual direction, a general TRTF may be sufficient. This general TRTF will at least compensate for the bias toward the midsagittal plane.

The results imply that optimal performance may be expected for tasks that require the perception of directions straight ahead or straight behind. This is the case in a situation in which a visually handicapped individual wants to walk to the next waypoint in a preprogrammed route, or a fighter pilot wants to fly toward a target. This also implies that tactile direction perception can be complementary to 3D sound, due to the fact that 3D sound is optimal in presenting lateral directions but has a relatively high occurrence of front – back reversals [4].

The available research has not addressed two important issues. First, it might be expected that tactile performance is different when the observer is allowed to move around; this is analogous to how slightly moving the head can improve auditory direction perception. In addition, investigations about direction estimations in a 2D transverse plane leave the question open if observers are also able to indicate accurate elevation based on a tactile stimulus on the torso.

3.1.1 Burst Duration and Timing Parameters

As discussed in Chapter 2, it is well known that localization is dependent on timing parameters [5 – 9], and the usefulness of spatiotemporal patterns thus depends on (location dependent) spatial acuity and on temporal parameters. To gain more insight into the processing of simple spatiotemporal patterns on the torso, a second experiment in Van Erp [1] concerned localization performance as a function of two timing parameters:

a) Burst duration (BD); and

b) Stimulus onset asynchrony (SOA).

The results showed that localization performance increased when the BD increased and/or when the SOA increased. This means that tactile display applications that require high localization accuracy can benefit from longer BDs and SOAs. On the other hand, tactile display applications that require fast presentation of (consecutive) stimuli, as in vehicle control applications, may require a larger distance between the tactors.

Apparent motion, temporal masking, and adaptation were also discussed in Chapter 2. The occurrence of apparent motion seems to enhance performance. The fact that the skin automatically integrates specific spatiotemporal patterns is likely to be important in designing such patterns. The effect may have both positive and negative effects, including spatial and temporal masking. Temporal masking can be prohibited by using different loci or frequencies (one below 80 Hz and one above 100 Hz), while adaptation effects can be prevented by switching between a frequency below 80 Hz and one above 100 Hz [10].

3.1.2 Tactile Illusions

There are tactile illusions that may be useful in tactile displays [11]. These tactile illusions use psychophysical properties of the somatosensory system to change the perceived intensity, location, or motion of the tactile stimulus. When two tactile stimuli of equal intensity are presented simultaneously to adjacent locations on the skin, the resulting sensation is not two separate tactile sensations. Instead, the stimuli combine to form a sensation midway between the two tactors. This illusion is called the "Phantom sensation" [12 – 15], and could be used to generate "virtual tactors" located between physical tactors, thereby reducing the number of tactors required in an operational tactile instrument. The phantom sensation is dependent upon the physical separation of the stimuli, the amplitude, and the timing of the stimuli. A second relevant illusion is that of apparent motion. Depending on the temporal parameters, the sequential activation of spatially separated tactors can elicit the sensation of smooth, continuous motion from the first activated tactor to the last activated tactor (see Chapter 2 for details on apparent motion).

3.2 CODING PRINCIPLES

Stimulus characteristics can also be utilized to present specific types of information to the user. Coding principles are used to create easily discernable tactile messages and multi-information displays. Often, two or more coding principles can be used to create an intuitive tactile signal. As tactile displays become more widely used, coding standards must be considered for particular uses. For example, different approaches can be taken to counter spatial orientation regarding altitude, roll, pitch, and yaw of aircraft (see Chapter 6 for applications). Tactile characteristics include size, shape, orientation, position, moving patterns, frequency, amplitude, rhythm, and waveform. These characteristics are listed below and summarized in Table 3.1.

Table 3.1: A Summary of the Properties of Nine Tactile Characteristics

Characteristic	Properties
Size	– Limited number of distinctive levels – Large difference between sizes preferable – A clear boundary is needed – Simultaneously displayed sizes is feasible
Shape	– Fair number of distinctive levels – Similar tactile shapes should be avoided – A clear boundary is needed – Simultaneously displayed shapes is feasible
Orientation	– Limited number of distinctive levels – The shape should not be rotational symmetric – A clear boundary is needed – Simultaneously displayed shapes is feasible
Position	– Many distinctive levels possible – Large distance between displays preferable – Simultaneously displayed positions is highly feasible
Moving patterns	– Any distinctive levels possible – The moving patterns should be quickly recognizable after their start – Simultaneously displayed moving patterns is moderately feasible
Frequency	– Limited number of distinctive levels – Low feasibility for simultaneously displayed frequencies
Amplitude	– Limited number of distinctive levels – Low feasibility for simultaneously displayed amplitudes
Rhythm	– Many distinctive levels possible – The rhythms should be quickly recognizable after their start – Low feasibility for simultaneously displayed rhythms
Waveform	– Includes square, triangular, saw tooth, and sine waves – Requires sophisticated hardware

3.2.1 Tactile Characteristics

3.2.1.1 Size

Size refers to the overall surface area that the tactile display uses to depict the information. A small square of tactors might be activated to depict a low-priority threat, while a larger square centered at the same location could represent the location of a high-priority threat. Size can be used to create a limited number of distinctive perceptual levels that are more easily distinguished when the boundaries of the depicted patterns are better defined. This requires small tactors in a high density configuration, which may not always be possible.

3.2.1.2 Shape

The shape of a tactile symbol depends on having a clearly defined boundary. The number of distinctive shapes that can be created is dependent on the number of tactors in the display. It is possible to display an enemy aircraft as an “x” and a friendly as an “o”, but little data exist on how easy it is to distinguish different symbols created with tactors.

3.2.1.3 Orientation

Orientation of a tactile symbol can also be varied to provide information to the wearer. An enemy threat might be depicted as a vertical line of three tactors, while a friendly aircraft could be depicted as a horizontal line of three tactors. It is unclear if these types of displays are easily discernible in an operational setting.

3.2.1.4 Position

Position is probably the most used and most intuitive characteristic to utilize during tactile coding, especially if the coded information concerns spatial information. The advantage of position is that it can be used to create many distinctive perceptual levels as long as the distance between two neighboring positions is large enough and the positions do not overlap. It is feasible to present multiple targets at different positions on a tactile display, and it is even possible to utilize different locations on the body to attach two or more position-based tactile displays. For example, navigation information may be displayed on the frontal part of the torso, while threat information is displayed on the dorsal side. A similar principle can be used to display horizontal directions to, for instance, dismounted soldiers by using two tactile belts. The lower belt may present navigation information while the upper one presents critical communications. This may, however, cause cognitive overload or attention tunneling that will be discussed later in this chapter.

3.2.1.5 Moving Pattern

Another characteristic that can be used to create many distinctive perceptual levels is moving patterns. A moving pattern is a time-varying shape that can create sensations of movement. The moving pattern should be designed such that it can be distinguished from other moving patterns quickly. One example of using moving patterns is for communication. One row of tactors is rapidly activated in succession to create a sensation of moving around the wearer. This circumferential pattern has been used to communicate to soldiers to “rally to the left” or “rally to the right” [16, 17]. Another suggested use is to create a flow field that might mimic how the wind feels when moving forward or in a specific direction (e.g., Van Erp et al., [18] used flow patterns to display helicopter direction and speed in a low-hover task).

3.2.1.6 Frequency

The frequency at which particular tactors are activated can also be used to convey information. In the hairy skin, there are three different types of mechanoreceptors that can be activated at specific frequencies (see Chapter 2). However, at suprathreshold stimulation more than one channel will be activated at the same time [10, 15, 19 – 22] . Within each tactile channel, only a few discernable levels of frequency can be created. This may limit using different frequency levels as a way to convey different types of information.

3.2.1.7 Amplitude

The amplitude of the stimulation can also be varied. This results in a stronger sensation, because more mechanoreceptors are activated [23]. The disadvantage of this dimension is that only a few discernable levels can be recognized. The number is further reduced, because stimulation amplitudes just above the detection threshold are normally not used.

3.2.1.8 Rhythms

Users can discern many distinctive levels in rhythms, and humans can replicate rhythms presented in the tactile modality better than presented in the visual modality [24, 25]. Different patterns in rhythms are often called tactons [26]. Tactons can be defined as specific tactile patterns or a series of tactor actuations

that refer to a specific image, object, or action. In effect, one can relate tactons to a type of Morse Code that is presented by tactile means rather that auditory or visual means. To create rhythms, a tactor vibrating at a constant frequency is switched on and off rhythmically. If amplitude and frequency of the signal are also varied, tactile melodies can be created, differing in intrusiveness and tempo [27]. The rhythms should be quickly recognizable, but discrimination between simultaneously presented rhythms can be difficult. Using different tactons to convey different types of information is very valuable in coding tactile information.

3.2.1.9 Waveform

Different patterns of the activation amplitude can also be presented to convey different information. Examples of this include using square, triangular, saw tooth, and sine waves. The sensation created by each waveform is dependent on the frequency and amplitude of the signal, and the tactor must be very precise to create the specific waveforms listed. While each type of waveform is perceived quite differently, the need for sophisticated hardware to create each waveform probably precludes using it as a primary means to provide different types of information.

3.2.2 Multiple Information Displays

As increasing amounts of information are being conveyed to the user in a growing multitude of land, air, and sea environments, it is often desired to convey more than one piece or type of information. The characteristics discussed above can be used to provide different types of information to the user. Although it is technically feasible to display multiple pieces of information simultaneously within a single tactile display, the design must be carefully considered. A study conducted by McKinley et al. [28] used three different tactile patterns or tactons to present the type of target aircraft (enemy, unknown, and friendly) to the pilot. The location of the tacton on the tactile vest indicated the position (azimuth and altitude) of the target aircraft relative to the participant's own aircraft. Because targets rarely appear alone, three targets were displayed simultaneously. The experimental results combined with subjective feedback from the participants indicated that it was difficult to differentiate between the tacton indicating an unknown type aircraft and the tacton indicating an enemy type aircraft. This was largely due to the fact the first half of the tactile pattern used for the unknown aircraft was the same as that used for the enemy aircraft pattern. This was also observed during the development of tactons to represent Army hand and arm signals – patterns that started with the same tactor and began with a similar pattern were more often confused and/or took longer for accurate identification [17]. Hence, when designing a tactile display that will provide multiple pieces of information simultaneously, it is important to ensure each tacton used is clearly identifiable and categorically different than the other tactons (see Section 3.1 on perceptual issues).

Additional issues that should be considered in multiple information tactile displays include the notion of overlap and tactile resolution. For example, it is currently not possible to clearly present two different tactons simultaneously at the same location of the body. This indicates that the design should carefully consider what information needs to be displayed as well as how the information should be prioritized. For example, in the case of presenting aircraft target information to the pilot, it might be possible for two different types of aircraft to reside in close proximity. Hence, the two patterns would overlap on the same part of the body. Van Erp et al. [27] introduced the term tactile clutter for this effect (please note that visual and auditory displays face the same challenge). A possible remedy is to only present the tacton for the aircraft that poses the greatest threat. In addition, it should be noted that the number of items that can be presented on a single display largely depends on the number of tactors available. The other tactile display characteristics in Table 3.1 may also be used to convey multiple targets or types of information, but characteristics such as size, shape, and orientation are also highly dependent on the number of tactors. Consequently, tactile displays utilizing few tactors will not have the capacity to provide multiple pieces of information simultaneously.

3.2.3 Coding Standardisation

Often, two or more coding principles can be used to translate the information into a tactile 'picture'. For instance, two self-motion coding principles have been applied to help counter spatial disorientation in pilots [29]. These principles resemble the inside-out and outside-in concepts, also recognized in the design of the artificial horizon display. Inside-out coding of yaw rotation (i.e., rotation around the vertical axis) can be realized by a tactile signal pointing to a fixed direction in the outside world. This means that the tactile signal rotates clockwise when the pilot rotates counter clockwise, and vice versa. In the outside-in coding alternative, the signal rotates on the display in the same direction and with equal velocity as the pilot rotates in the outside world; it is the same speed but opposite direction of the inside-out display. An important advantage of the inside-out coding is that the position of the tactile signal on the display is Earth-fixed and thus also congruent with out-the-window visual information. This may have beneficial effects on the situation awareness of the pilot, while the outside-in coding may have benefits in control tasks. As with visual displays [30], the preferred coding on the tactile display is most likely task dependent.

It should be noted that the lack of guidelines on the design of tactile cockpit displays has already resulted in the use of different coding principles in the design of a helicopter hover display. Van Erp et al. [31] coded the direction of drift in a helicopter hover display using a 'follow the needle' principle. The pilot had to follow this "command" tactile signal as if it indicated the next waypoint. Raj et al. [32] coded the direction of drift using a "status" algorithm, which means that the pilot had to steer away from the stimulus as if the pilot bounced against a virtual wall. In the first coding algorithm, the vibration unambiguously indicates the optimal direction of motion. The virtual wall analogy indicates the direction to avoid, which leaves the pilot with the choice to determine the optimal steering action; many motion inputs will free the pilot from the wall.

Dobbins and Samway [33] mention this same issue in coding a virtual corridor on a tactile display to support course control in operating high-speed powerboats. Although there are no data available that directly compare performance with both codings, one may expect that performance may degrade if the pilot has to switch between codings. This latter issue was also found with pilots who transferred from an outside-in to an inside-out coding of the artificial horizon [34].

3.3 COGNITIVE ISSUES

Determining the appropriate coding principles to use for an application does not guarantee that the user will be able to fully comprehend the information that is provided in a tactile display. Two issues that are present in both visual and auditory displays must also be considered in the tactile modality: attention tunneling and cognitive overload.

3.3.1 Attention Tunneling

Attention tunneling refers to a narrowing and general lessening of attention such that perception is reduced to a narrower band of information relative to available cues. Wickens [35] provides the definition of attention tunneling as "the allocation of attention to a particular channel of information, diagnostic hypothesis or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks." Note that the definition must include both the forces that "lock the tunnel" to its current channel, as well as a definition of a channel of neglect. The US Air Force identified attention tunneling as being a major cause of F16 mishaps, and a great many aviation accidents in general can be associated with attention tunneling away from important altitude information [35]. Wickens identified four different factors affecting attention tunneling in pilots: head up display location, the compellingness of 3D displays, fault management (e.g., "fixating" on a single problem), and automation (e.g., complacency).

Attention tunneling can be brought about in situations of sustained attention and fatigue. A common experience is that of long-distance driving, where the driver focuses attention on the road immediately ahead, and is less attentive to peripheral cues. The same phenomenon can be generalized across many long-duration operational situations, particularly when attentional demands are low. In this case there may be too much automaticity and arousal/stimulation or higher attentional requirements could be more effective [36]. Automaticity is closely and reciprocally related to the difficulty, mental effort, and attention resource demands of a given task [37].

In situations of long duration and high monotony, tactile cues may be most effective in arousing attention without the “override” associated with audio cues. Such cues may help to “break” the attentional fixation, especially if the modality has been “silent” during the majority of the task. Compared to visual warning signals, auditory and tactile signals have been found to be more effective at drawing cross-modal attention to particular positions [38]. Dynamic tactile information (e.g., five tactors placed on the forearm vibrating sequentially) was used to accurately reorient visual attention [39]. Tactile cues, or any attention-directing cues, should be designed to be recognized in parallel to ongoing tasks, to provide information on the significance of the interruption, and to allow for evaluation that does not require foveal attention [40]. In a study of U.S. Army command and control decision making, soldiers preferred the tactile cues to that of visual or audio alerts, stating that the tactile cue gained their attention better and faster than the visual icon, while not being as disruptive as the audio cues [41]. Further research is needed to investigate the effectiveness of using tactors for attention directing cues, particularly in long-duration situations of low workload and infrequent but critical information cues.

While situational awareness can decrease under low workload conditions due to boredom and complacency, it can also suffer under high workload situations [42]. Operators may fixate on solving a single problem during high workload, and tunnel their attention only to a single specific visual display. Tactile displays or alerting cues may help mitigate this problem. Tactile cues have been found to be effective in high-workload multi-task situations [43] and in dynamic, event-driven domains [44]. Of course, there is some danger that the operator could also become fixated on the tactile display. Some studies suggest that tactile perception may override perception through other sensory channels [4]. The use of a torso-mounted tactile land navigation device by soldiers should ideally free their “eyes, hands, and mind” to better attend to perception of terrain obstacles and potential threat. However, in long-duration night operation missions, will they instead simply fixate on the tactile cues? If this is the case, how can it be ameliorated? Many attention issues in tactile displays must still be investigated, from theory-based issues of attention management to more operational aspects that enhance performance in the field.

3.3.2 Cognitive Overload

Cognitive overload refers to an over demand of the (momentarily available) cognitive capacities of the user. Taking car driving as an example, evaluation of visual based information systems has shown that such systems may negatively influence the drivers’ scanning behaviour and attention allocation (i.e., they distract the driver [45]). Visual displays have a specific disadvantage when presenting three dimensional (3D) navigation information. Because the displays are flat or 2D, one (or more) dimensions must be compressed. This results in loss of information and usually requires cognitive effort to reconstruct the 3D picture from the 2D display. In the same way, meta-analytic investigations have found that listening and speaking during driving (e.g., using cell phones) are detrimental to performance, regardless of whether the cell phones were hands-free [46]. Although the driver may be able to *sense* all of the different input received, they may not be capable of *cognitively processing* all of the information into a coherent model of the surroundings.

There are many models on workload and navigation, including Sheridan’s model for supervisory (vehicle) control [47], Wickens’ information processing model [48 – 50], Veltman and Jansen’s workload

framework [51], and Rasmussen's framework on skill-based, rule-based and knowledge-based [52, 53] behavior. One of the most commonly accepted models is Wickens' Multiple Resource Theory, or MRT [48 – 50, 54], which can explain why tactile displays seem to be successful at providing information to the wearer.

The MRT predicts no performance degradation under normal workload when independent resources or information channels are used to present information. The MRT predicts, to some extent, concurrent processing of tasks. The concept of resource decomposition is of specific interest here. The resource decomposition concept states that task interference (i.e., performance decline) will only manifest itself to the extent that the two or more tasks share resources under conditions of high overall workload. Several researchers found that decrements in performance in multi-task-situations were not additive, as a single-resource theory predicts; instead, their studies suggested that the decrement depended on the degree to which the competing tasks also competed for the same information channel [48][55]. Time-sharing between two tasks was more efficient if the two used different information processing structures than when they used the same. This suggests separate information channels have, to some extent, independent resources that are still limited, but could function in parallel. This means that task interference will be reduced when the tasks' demands are maximally separated across resources. This separation can be along different resource dimensions such as sensory modality (including touch [56]) and verbal versus spatial processing codes. Since critical information in many applications is predominantly visual (e.g. for driving, see [57]), the MRT model would predict less interference of a second task when information is presented to another sensory modality – hence the introduction of tactile displays. Simply put, MRT proposes that:

a) People have several independent capacities with resource properties;

b) Some resources can be used simultaneously, some cannot;

c) Tasks using different modules can often be performed together; and

d) Competition for the same modality can produce interference.

Based on the principles of the MRT, tactile displays may reduce the threat of both sensory and cognitive overload. Because the sense of touch is a relatively underused modality in human-computer interaction, the threat of sensory overload through tactile displays is small. Thus, tactile displays may help reduce the chance of cognitive overload by utilizing a separate resource that is typically underutilized. Transferring information from visual displays, which are heavily used in high stress environments such as flying, to tactile displays may reduce the chance for sensory overload in the other senses. If the tactors are programmed effectively, the intuitive nature of tactile displays can be utilized. Interestingly, many of our reflexes are based on the sense of touch. An example is the rooting reflex in babies, that is, turning the head in the direction of a tactile stimulus to the cheek. A similar effect is found on the torso, which has been called the "tap-on-the-shoulder" principle [58]. A tap left draws and directs your spatial attention to the left. Additional advantages of the torso are its natural 3D form and its ego-centricity.

3.4 MULTISENSORY INTEGRATION

In most applications, tactile displays will be integrated with visual and/or auditory displays, making it necessary to understand how this multisensory information might be processed. In everyday life we see, hear, feel, smell and taste the world around us, and apparently without much effort we are able to integrate this continuous multimodal stream of information into coherent percepts. Even if the signals from the different senses are incongruent, our brain still tries to integrate the conflicting information in a sensible way, sometimes resulting in perceptual illusions. Crossmodal perceptual illusions vary from subtle changes in the interpretation of ambiguous stimuli to very robust qualitative changes in perception. In the 'bounce illusion' [59], two moving disks seem to bounce instead of crossing each other under the influence of a brief sound at the moment of collision. The 'visual motion illusion' is a change in

interpretation of the motion direction of an ambiguously moving grating induced by changing the auditory pitch level [60]. Besides these crossmodal effects on the interpretation of stimuli, even crossmodal alterations of perception of non-ambiguous stimuli are observed. Well-known examples are the McGurk effect, in which the perceived sound is modulated by an incongruently articulating mouth [61], the ventriloquist effect where sound is mislocalized towards the apparent visual source, and visual capture in which incongruent visual stimuli influence the localization of vibrotactile stimuli [62]. Shams [63, 64] discovered a 'visual illusion that is induced by sound: when a single flash of light is accompanied by multiple auditory beeps, the single flash is perceived as multiple flashes'.

Andersen et al. [65] discuss the relative dominance of modalities in light of four hypotheses; the *stimulus discontinuity hypothesis* [63], the *modality appropriateness hypothesis* [66], the *information reliability hypothesis* [67], and the *directed attention hypothesis* [66] . The stimulus discontinuity hypothesis states that a modality that has discontinuous stimulation will tend to dominate those with continuous stimulation. This hypothesis was offered to explain why a single brief flash of light was perceived as two flashes when accompanied by two audio beeps. According to the modality appropriateness hypothesis, the modality that is most suitable for a certain task dominates the other modality. Of course, it can be difficult to determine which modality is more appropriate for a particular task without resorting to circular arguments. Andersen argued that the modality appropriateness hypothesis should be considered as one of several factors defining the range within which a modality can dominate perception. The information reliability hypothesis asserts that the modality providing the most reliable information is dominant. The directed attention hypothesis states that attending to a modality influences perception. Andersen et al. propose that discontinuity, modality appropriateness, information reliability, and directed attention are all factors which contribute to the relative influence of each modality.

Recently Andersen et al. [68] proposed a Maximum Likelihood Integration (MLI) model for multisensory integration. They assume that multisensory integration occurs in an early stage of sensory processing, before stimulus categorization; therefore this model is referred to as early MLI. The model accounts for three of the above mentioned hypotheses that contribute to the relative dominance of each sensory modality. Both directed attention and modality appropriateness are interpreted in terms of information reliability. Directed attention to one modality increases the reliability of that modality and the sensory modality that is more appropriate for a certain discrimination task provides more reliable information. In the MLI model, the weights assigned to information in each modality are based on this reliability, hence the more reliable the information of a modality, the larger the relative influence of that modality in the integrated percept. Bresciani, Dammeier and Ernst [69] follow a similar approach, but use a Bayesian probabilistic model for multimodal integration that accounts for the coupling between the sensory estimates. These results indicate that even when one signal is explicitly task irrelevant, sensory information tends to be automatically integrated across modalities. They also suggest that the relative weight of each sensory channel in the integration process depends on its relative reliability.

It is anticipated that in the majority of applications the tactile display will support a primary visual display, and in some cases an audio display. In this situation the tactile display may reinforce the visual display by providing a warning signal, or may de-clutter a 'busy' visual display by displaying some of the information via a tactile display. Studies have shown that combining modalities can improve human performance in a variety of environments [4, 32, 37, 43]. Though much information concerning a discrete event (e.g., a warning) can be presented by a single modality, it is clear that the brain achieves a sum that is greater than the parts by integrating a multimodal warning across sensory modalities [70]. The central nervous system (CNS) sorts sensory signals to combine those likely to originate from the same source, thus strongly determining the final perceptual experience. The selection and combination of multisensory signals in the CNS can be considered an optimization process taking advantage of cue redundancy. This has been shown to reduce the variance of perceptual estimates and to enhance stimuli detection [71]. Thus, combining modalities offers an opportunity to take advantage of multimodal presentation of intuitive and redundant cues. These intuitive and redundant cues can (in many cases) deliver information

that allows an operator to better manage important information. There are many examples of how perception can be enhanced or biased by the integration of multisensory signals; the following is provided by Moorhead et al. [72]:

> "Low contrast or noisy visual and sound stimuli can be combined to improve spatial localization. On the other hand a salient visual stimulus can readily 'capture' the perceived origin of a sound, as occurs when we view a ventriloquist [73]. Being able to see ones arm improves the spatial resolution of tactile discrimination when two (unseen) pinpoint stimuli are applied near one another on the skin [74]."

In conclusion, multimodal interfaces can be important in assisting perceptual decisions, and may represent the spatial dimension in a more direct, natural, and intuitive manner [4].

3.5 USER ACCEPTANCE

It is reasonable to expect that user acceptance and trust will depend on equipment accuracy and reliability. Automation reliability is an important determinant of human use of automated systems because of its influence on human trust [75 – 77]. When information is uncertain, the level of uncertainty should also be communicated to the operator, otherwise trust will be affected. Certainly, practice and familiarity with a reliable and accurate system will affect trust. When tactile in-car displays were utilized in an automobile driving task, drivers had to learn to trust the tactile device [78]. In another example, Army soldiers moved much more quickly once they learned they could rely on the tactile land navigation device to guide them to their waypoint, and that the tactile device can "keep up" regardless of their speed [79].

In addition to accuracy, reliability, and familiarity, another determinant of user acceptance is ease of use. The ease of use is highly dependent on making tactile messages self-explanatory [24]. Another aspect determining ease of use is how intuitive it is to interpret the display information. The display of information should match with the sense that is the most intuitive. For example, in response to numerous aviation accidents caused by spatial disorientation, engineers added more visual displays for pilots. However, this did not reduce the occurrence of accidents, partially because the visual channel was overloaded (so the new information was not being processed). In contrast, the tactile cues were more naturally interpreted as orientation cues compared to visual cues [80]. In addition, given a particular sensory channel, displays can be designed that are more or less intuitive with regard to task demands. For example, torso-mounted tactile cues have been found to be very effective as direction cues for navigation and direction cues (i.e., target detection) when the soldier is in the natural environment (e.g., moving or looking in the same direction as the cue [79]). However, they were less effective when used for target detection in a computer simulation task as compared to a visual icon that was particularly suited to specific task demands [81]. In another investigation, tactile cues were compared to 3D audio in a visual search task, and were not found to be as effective. However, this investigation utilized three tactors (indicating left, middle, and right) which were placed side-by-side on the forearm. This was a much less intuitive display for direction information than a belt or torso display. When used for land navigation, soldiers reported higher levels of satisfaction ("satisfied" to "extremely satisfied") with the ease of use and preference for the tactile system, relative to existing Army navigation systems. Most frequently cited reasons for preferring the system was that it was hands-free (thus allowing the soldier to keep their weapon ready), intuitive (e.g., easy to follow signals, "idiot-proof") and accurate (e.g., leading directly to the waypoint).

Ease of use can be indicated by short training times and high levels of automaticity in performance. Soldiers effectively used the tactile land navigation system after a five minute hands-on demonstration [79]. In an investigation of torso-mounted tactors for communication, soldiers readily learned and distinguished five tactor-based patterns for communicating common arm-and-hand signals (halt, rally, move forward, attention, NBC alert) after five minutes of practice. This was likely due to careful

development of the tactile patterns to match the arm-and-hand signal patterns. In fact, participants (Army cadets) who were simply given the tactile signals and the five choices of hand signal, but were not told which tactile pattern represented which hand signal, guessed the correct representation 51% of the time. After 5 minutes training, another group performed with 71% accuracy [82].

3.6 SUMMARY

Human factors issues will play a major role in the design and implementation of any tactile display. Designers must consider the psychophysics of touch, described in Chapter 2, as well as a myriad of perceptual factors. Both sensory and cognitive overload must be avoided, and theories such as Wickens' Multiple Resource Theory should be consulted when developing multisensory and multi-function displays. Finally, coding principles to convey tactile information were discussed. It should be clear to the reader that there are numerous human factors issues when designing tactile displays, and while there are many emerging principles to guide display design, there are also many avenues that need further investigation. Chapter 4 identifies and describes the hardware to actually implement and investigate these principles.

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Chapter 4 – TACTILE ACTUATOR TECHNOLOGY

by

B. McGrath, A. McKinley, M. Duistermaat,
O. Carlander, C. Brill, G. Zets and J.B.F. van Erp

Over time, a wide variety of tactile stimulation devices have been designed and implemented in an attempt to minimize power requirements and weight while simultaneously maximizing the stimulus effect. Consequently, the hardware is widely varied and has specific strengths and weaknesses. This section discusses the basic features universal to particular tactile actuator (tactor) designs and a summary table indicating the key performance characteristics of each technology. In addition, there are several characteristics that must be considered when attempting to optimize the tactile actuator design. When considering the signal itself, it is important to take into account its strength/amplitude, the amplitude range, power consumption, and the frequency range. Ideally, the available frequency range and stimulus amplitude range should match that of the human sensory system (see Chapter 2) and its perceptual characteristics (see Chapter 3). Conversely, the power consumption should be kept to a minimum, especially when there is a need for portability. In addition, it is ideal to reduce the size/weight of the individual tactors, physical discomfort, distortion of the signal, and any sensitivity to contact pressure. Likewise, there is a need to maximize the reliability of the hardware, improve its ruggedness, and provide the option to protect electrical components from water. Lastly, the amount of acoustic energy and electromagnetic radiation should be kept to a minimum. However, it should be noted that some of these design requirements are specific to the type of tactor technology. For example, purely electrical stimulation typically does not yield acoustic energy radiation. These aspects are discussed in greater detail in the following sections.

4.1 ELECTRICAL

Electrical tactile systems provide the sensation of touch through electrotactile excitation. Also known as electrocutaneous stimulation, this technology uses tiny electrodes to produce stimulus-controlled, localized touch sensations by passing a small electric current through the skin. The electric field generated then excites the neighboring afferent nerve fibers responsible for normal mechanical touch sensations. The elicited sensation can be described as a tingle, pressure, vibration, or pain, depending on the electrode and waveform properties. The system typically produces voltage-based pulses and offers control of several signal characteristics including voltage amplitude, frequency, duty cycle, and polarity. The individual tactors can be constructed with any conductive material including metals and conductive rubber. Because there are no moving parts or mechanical functions, the overall weight and size are markedly reduced and the reliability of the tactors is improved in comparison to mechanical tactors. An additional benefit is that the sensation is very localizable allowing for high density tactile arrays over a relatively small surface area. An example of this type of tactile system is the experimental transcutaneous electrical nerve stimulation of orientation research (EXTENSOR) pictured in Figure 4.1.

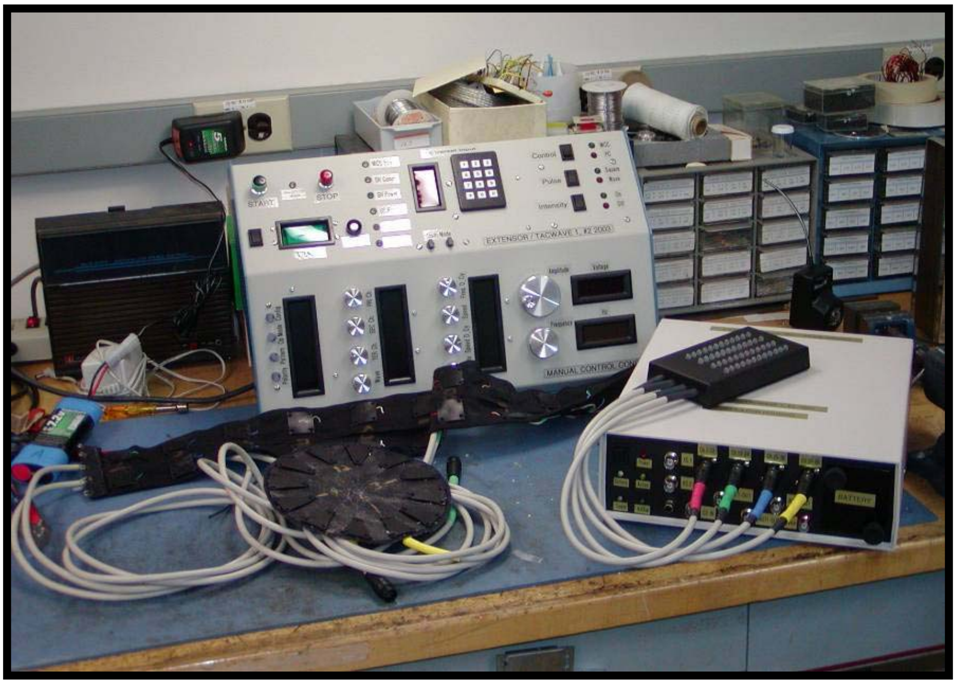

Figure 4.1: EXTENSOR Electrical Tactile Stimulation System.

Widespread use in the scientific and operational community to utilize electrical tactors has not occurred probably because of the more common use of vibro-mechanical systems. Also, the skin condition has a profound influence on the dynamic range and comfort of the stimulation. Dry skin yields high impedance and a prickly sensation, which is most likely due to the inconsistent current distribution. This often can be alleviated with the use of an electrolyte gel or saline solution. Although this functions well in the laboratory, it is currently not acceptable for the operational environment. Even with ideal parameters, small changes in electrode position can greatly alter the sensation and pain thresholds. In addition, the tactor's contact with the skin must remain constant to maintain the same sensation. Furthermore, the psychological condition and training of the subject can vary the threshold of pain. Experienced subjects can sometimes tolerate twice the stimulation levels of naïve subjects. Figure 4.2 displays examples of the tactile arrays that utilize electrodes made from conductive rubber.

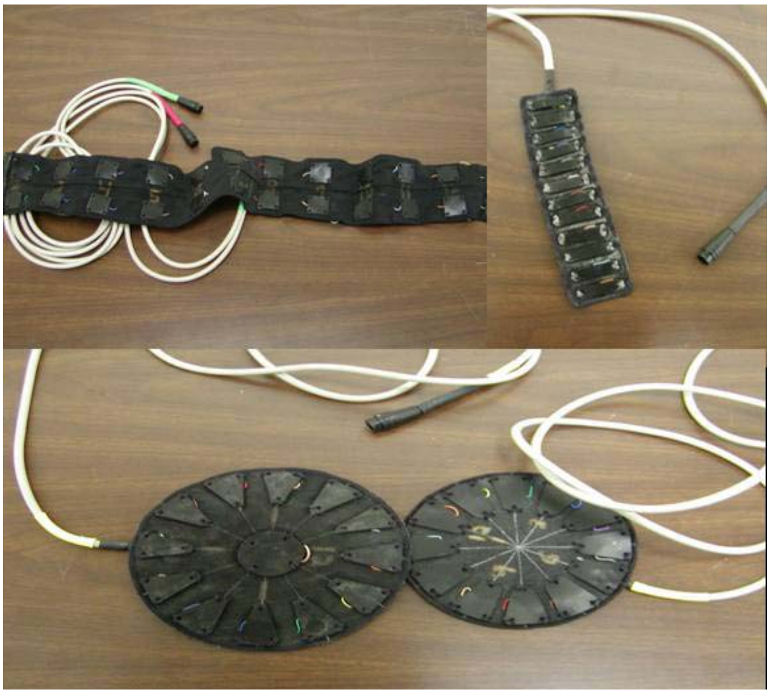

Figure 4.2: EXTENSOR Tactile Array Examples using Conductive Rubber.

4.2 VIBRO-MECHANICAL

4.2.1 Electro-Mechanical

4.2.1.1 Rotary Inertial

The rotary motion tactor consists of a housing incorporating a motor with an eccentric mass. The rotation of the motor causes the housing to vibrate, causing stimulation to the skin. The best known example of the rotary-inertial tactor is the pager motor found inside cell phones. The housing does not have to make direct skin contact; clothing can be worn in between the skin and the tactor, although this depends on the intensity and frequency of the specific motor and the type of housing that are used. However, for optimal signal transfer the tactor should be as close to the skin as possible.

The majority of rotary-inertial tactors are based on commercially available pager motors placed inside a custom housing. For example, the OPTEC-2890W11 is a commonly used motor for tactile stimulation and is pictured in Figure 4.3.

Figure 4.3: OPTEC-2890W11 Pager Motor.

The rpm of the motor defines the tactile frequency stimulus and is typically in the range of 4000 – 9000 (i.e., 70 – 150Hz). These "pager-motor" tactors are increasingly made in-house by the laboratories undertaking research work. For example, TNO (The Netherlands) and FOI (Sweden) have produced custom rotary-inertial tactors for specific tactile applications (e.g., presenting navigation, targeting, or orientation information), and include custom housings and custom drive electronics. The TNO and FOI specialized tactors can be found in Figures 4.4 and 4.5, respectively. The size, cost, robustness, and low power characteristics of the "pager-motor" tactor make it a popular choice for many applications.

Figure 4.4: TNO Custom Rotary-Inertial Tactor (Left). TNO Tactor Array Housed in Vest (Right).

Figure 4.5: FOI Sweden Tactile Belt – 12 Tactors Evenly Spaced Around Torso.

4.2.1.2 Linear Actuators

Linear actuator tactors are miniature, coil based actuators that have been optimized for use against the skin. Linear actuator tactors can incorporate a moving "contactor" that is lightly preloaded against the skin or can be embedded in a closed housing. When an electrical signal is applied, the "contactor" or housing oscillates perpendicular to the skin. In case of a moving contactor, the surrounding skin area can be "shielded" with a passive housing. This provides a strong, point-like sensation that is easily felt and localized. Linear, coil-based actuators have good frequency and amplitude control in the range around their resonance frequency.

Examples include the B&K 4810 minishaker, the Engineering Acoustics Incorporated (EAI) C2 tactor, the Audiological Engineering VBW32 tactor and the Special Instruments Minivib-4 tactor (see Figure 4.6). For optimum vibrotactile efficiency, the latter three tactors are designed with a primary resonance in the 200 – 300 Hz range, which coincides with peak sensitivity of the Pacinian corpuscles (cref Chapter 2). Recently, EAI has begun manufacturing a low frequency version of the C2 tactor (designated the C2-LF), which operates in the sub 100 Hz range. Linear actuator tactors high force and displacement level allow the vibration to be easily felt at all locations on the body, even through layers of clothing.

Figure 4.6: C2 Tactor (Left, Engineering Acoustic, Inc.) and Minivib-4 (Right with Housing Partly Removed, Special Instruments, Sweden) are two Examples of Coil Based Linear Actuators.

4.2.2 Pneumatic Tactors

Pneumatic tactors are a form of linear actuators that typically consist of a "hard" shell/reservoir with a "soft" membrane covering the opening of the shell. An air supply tube attaches to the plastic shell. Oscillatory compressed air is driven into the plastic shell that forces the soft membrane to vibrate. Oscillatory compressed air signals are typically generated by sub-miniature solenoid valves connected to either a compressor or pressurized air tank. An example is the Steadfast Technologies P2 tactor. The P2 tactor uses a pressure of approximately 40PSI and a flow of 1 L/min. A valve block typically contains the valves, air manifold, controls and connectors, and needs to be mounted as close as possible to the tactor to reduce energy loses in the air supply tubing. These tactors are robust, lightweight and produce a strong intensity tactile sensation when the tactor membrane vibrates at 40 – 50 Hz. Pneumatic tactors have been integrated into the Tactile Situation Awareness System (TSAS) [1], a tactile display for presenting spatial orientation information to pilots. The tactors are integrated into a flight cooling vest and are "powered" by the existing pressurization systems for G-suit inflation.

4.3 OTHER TACTORS

4.3.1 Static Low Frequency Tactors

4.3.1.1 Pin-Based Tactile Displays

Pin-based tactile displays consist of dense arrays of metallic pins embedded into a surface. The pins are arranged spatially into a grid, and textual or graphic information is impressed into the skin via the heads of the pins. The result is that users are presented with the Gestalt of the spatial patterns, much as what happens when viewing pointillist works of art. A prominent example of this type of display is the

Optacon, a vibrotactile display originally developed for displaying text characters onto the fingertips of blind users. Text materials are scanned into the Optacon system, and the pins in the array vibrate against the skin using spatial patterns consistent with the shapes of the characters. A similar type of vibrotactile fingertip array was developed by Exeter. Vibrotactile fingertip displays are generally efficient, low-powered systems, as the fingertip is among the most sensitivity parts of the body. However, not all pin-based arrays use vibration. For example, ABTIM's VideoTIM operates in a manner similar to that of the Optacon, but it is based upon feeling the differential displacement of the pins in the array. On a much larger scale, the National Institute of Standards and Technology (NIST) developed a large graphical display using the same general principle.

4.3.1.2 Hydraulic

Similar to the pneumatic tactor, the hydraulic tactor uses fluid as the working medium. An example is a system developed by QinetiQ to produce a system for use in the Diver Reconnaissance System (DRS). The system uses an electric motor (24V dc, 400mA) to drive a piston which forces fluid into the DRS handles which expand and contract to provide the tactile / haptic stimulus to the diver's hands. The typical frequency range is 1 – 5Hz with large amplitude displacements of up to 25 mm.

4.3.2 Piezo-Electric Based Devices

Piezo-electric based devices are a linear actuator or linear inertial type tactors. These tactors use the properties of piezo-electric materials to produce the vibratory stimulus as opposed to the traditional electronic/magnetic motor design. The high cost, low force and displacement coupled with high voltage requirements have prevented widespread use. However, the non-magnetic properties of piezo-electric materials make it a possible solution in environments where magnetic materials must be avoided (e.g., mine counter-measures and the magnetic resonance imaging environment). The commercially available Thunder™ actuator (www.face-int.com/thunder) is one example of this type of device.

4.4 FUTURE TECHNOLOGIES

4.4.1 Electro-Active Polymers

Electro-active polymers (EAP) are a category of smart materials that are polymer based and react in the presence of an electric current. Typically these materials contract, expand or bend to a limited extent when an electric current or voltage is applied to them. However, new EAP materials contract by 20%, and will be available for research in the 2008 timeframe. Further information on EAPs can be found at www.ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm.

4.4.2 Micro-Electro-Mechanical Systems

Micro-Electro-Mechanical Systems (MEMS) integrates mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilisation of micro-fabrication technology. The electronics are fabricated using integrated circuit (IC) process sequences, and the micro-mechanical components are fabricated using compatible processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. Miniswys is a MEMS device that can produce rotary or linear motion; further information can be found at www.miniswys.com.

4.5 TACTOR PERFORMANCE MEASUREMENT

No standard device exists for the testing and comparison of various tactor types. Tactor performance and usability depends upon a large number of variables, which are closely related to many of the coding principles discussed in Chapter 3. These factors include:

- Magnitude – Peak-to-peak amplitude of the mechanical/electrical output signal;
- Frequency – Number of cycles per second at which the tactor stimulus operates;
- Waveform – Descriptive shape of stimulus pattern (e.g., sine wave, square wave, saw tooth);
- Pattern – Set of ordered, repeating stimulations;
- Duration – Time interval the tactor is active;
- Location – Position on the body where the tactor stimulates the tissue;
- Contactor Size – Surface area of the electrode or displacement (moving) portion of the tactor; and
- Interstimulus Interval – Time interval between the conclusion of one tactile stimulation and the beginning of the next.

The absence of standard test devices and the large number of variables that need to be controlled has prevented the comparison of different tactors. This includes comparing similar tactors from different manufacturers and comparing different types of tactors (pager motors, pneumatic, electric). However, the following two techniques have been used to quantify tactor performance.

4.5.1 Artificial Skin Model

The mechanical impedance characteristics of the skin can be simulated with an artificial model of the skin [2]. Using artificial skin models constructed of viscoelastic materials with embedded load transducers and displacement sensors, the force and displacement characteristics of a tactor can obtained. EAI and Steadfast have produced examples of the artificial skin model for tactor comparison. Further information is available at www.eaiinfo.com.

4.5.2 Human Comparison Studies

A tactile device (shaker) made by Bruel & Kjaer is used as a standard tactile reference (see Figure 4.7). The standard shaker is mounted so that the subject can rest his/her forearm on the tactor. The tactile device to be evaluated is typically mounted on the other arm/hand or on the lower back. The experimental tactile device is actuated, followed by the standard shaker. The subject then adjusts the frequency and amplitude of the standard shaker and repeats the sequence. This pattern continues until the subject has adjusted the intensity of the standard shaker to match the intensity of the experimental tactor. Audio and visual distractions are minimized using headphones and dark rooms. Raj et al. [3] used this technique to compare different type of tactors.

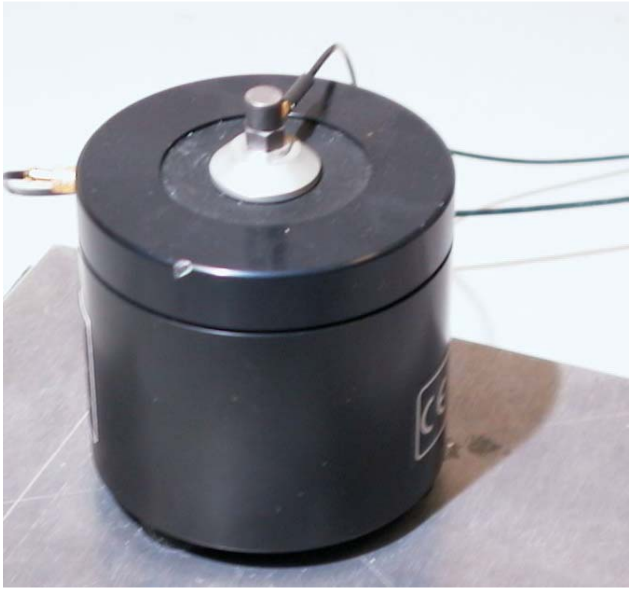

Figure 4.7: B&K Mini-Shaker, Type 4810 is a Coil-based Actuator that has an Extremely Wide Range in Frequency, Amplitude, Force, and Displacement.

4.5.3 An International Standards Organization (ISO) Standard for Tactile/Haptic Interfaces

A considerable amount of tactile research has been performed, but the lack of ergonomic standards in the area results in serious difficulties for users of multiple, incompatible or conflicting tactile/haptic devices/applications. Therefore, a set of ISO standards is being developed for inclusion in ISO 9241 Ergonomics of Human-System Interaction by a working group of ISO TC159/SC4 (WG9 Tactile and Haptic Interactions). These standards will provide ergonomic requirements and recommendations for haptic and tactile hardware and software interactions. This will also include guidance related to the design and evaluation of hardware, software, and hardware-software interactions [4].

4.6 TACTOR PERFORMANCE

Generally, the types of sensations one can present are limited to the capabilities of the device. Pager motors are an attractive option for vibratory stimuli due to the fact that they are small, lightweight, and very inexpensive (typically < $1 each, without custom made housing). To achieve strong sensations for relatively insensitive parts of the body or through multiple layers of clothing, two or three motors can be used concurrently. For applied research in which somatosensory cues are merely representative of future integrated equipment, pager motors are typically sufficient. However, these motors have several limitations. First, many models are manufactured for circuit board mounting (making them relatively fragile), and hand wiring these models with secure connections can be quite challenging. Second, because they are eccentric motors, frequency and amplitude are inextricably tied. In practical terms, this means that additional power equates to higher rpm, which yields a stronger sensation (i.e., in their usual operational range). This inflexibility limits their utility for laboratory research. The problem is further compounded by the fact that it is difficult to precisely describe the nature of the stimulus for the replication of research. Third, pager motors take time to “spin up” to full intensity. Consequently, the sensations evoked can be perceived as having a “soft start” rather than an abrupt onset. For presenting perceptual phenomena requiring precise timing (such as the cutaneous rabbit effect – cref Chapter 2), the soft onset of pager motors can be problematic.

Electromechanical transducers (linear actuators) are another form of tactor commonly used in displays. They are essentially specialized “speakers” with a moving element that contacts the skin. Most are made to operate in the limited frequency bandwidth of the skin (generally 20 – 500 Hz). They tend to be larger and heavier than pager motors and require more power than these motors. This is not a significant consideration for laboratory research, but is certainly a concern for field research and portable systems. With these drawbacks, why would one opt for an electromechanical tactor over a pager motor? The answer is twofold. First, electromechanical tactors are more robust than motors and capable of much stronger stimulation. Second, and more important to the research environment, they offer a much greater degree of control. Frequency, intensity, and to a certain extent, waveform, can be controlled independently of one another. This increases the variety of stimuli that can be presented.

Table 4.1 offers a summary of characteristics of the most common types of tactile actuators.

Table 4.1: Summary Table (Common Tactile Actuators)

Tactor	**Electrical**	**Vibro-Mechanical**	**Vibro-Mechanical**	**Vibro-Mechanical**
		Rotary Motion	**Linear Actuator**	**Pneumatic**
Size	The tactors can be made to be any size desired.	Typically a cylinder 14 mm long dia. 6 mm	contact surface 20 – 30 mm circular or square 8 – 10 mm thick	10 – 25mm dia. 5mm thick
Weight	Less than 5g, but variable depending on size of tactor	Typical motor 5 – 10g (housing dependent)	5 – 20g	0.8 – 2.0g
Frequency	8 – 500+ Hz	typically up to 160 Hz	1 – 300Hz, Optimized 200 – 300 Hz	0 – 100Hz, Optimized 50 Hz
Displacement **Amplitude**	Not applicable	Mounting dependent for tactor	up to 10 mm peak	3mm peak
Onset Time	Negligible/Immediate	50 – 80 msec to full amplitude	5 – 30 msec	<20msec
Axis	Not applicable	Rotary, perpendicular, mounting dependent	Perpendicular	Perpendicular
Power	3 – 130 volts, power based on impedance of skin	0.05 – 0.2 W	0.2 – 1.0 W	11 W (Compressor)
Linearity	Not applicable	Amplitude and frequency are linked	+/- 1 dB to peak displacement	Unknown
Drive Waveform	Any waveform, sine wave or square wave most common	Direct Current (DC)	Nearly any waveform, sine wave typical	Any waveform, square wave typical
Sensory Specificity	Capable of exciting all 6 identified tactile nerve receptors	All mechanoreceptors sensitive to vibration	All mechanoreceptors sensitive to vibration	Mechanoreceptors sensitive to low frequency vibration
Punctateness*	High – Very High	Medium, housing dependent (larger housing – more diffuse)	Dependent: high with protruding parts, medium with vibrating housing	Medium
Mounting/	On skin or sewable. Attachable via snaps, clasps, Velcro, and adhesives	Velcro, snaps, pockets, belt, vest, seat, cushion,	On skin; velcro, sewable flange, clip in holder in belt, vest, seat	On skin; sewable flange in belt, vest, seat

Tactor	Electrical	Vibro-Mechanical Rotary Motion	Vibro-Mechanical Linear Actuator	Vibro-Mechanical Pneumatic
Tactor Locator System				
Cost	$0.25 – $1.00, depending on conductive material	Typical pager motor < $20. Tactor cost $10 – $100, housing dependent	$ 50 – 200	$60 includes tactor, valve. Does not include compressor
Robustness	Suitable for most applications except underwater	Suitable for most applications, including harsh environments	Suitable for most applications, including harsh environments	Suitable for most applications, including harsh environments
Availability	Immediate	Immediate	Immediate	Immediate
Endurance	Indefinite	Years	Unknown	Unknown
Maintainability	None	Minimal, housing dependent	None	Minimal
Signature	None	High, housing dependent	Slight to moderate audio signature, Magnetic	Slight to moderate audio signature
Material (Outer)	Conductive rubber or tin	PVC and other polymers, aluminum, fiberglass	Aluminum, Polyurethane	Plastic, latex
Usability	Direct skin contact	No special requirements	No special requirements	No special requirements
Scalability	Can be used in multi-element tactile displays	Can be used in multi-element tactile displays	Can be used in multi-element tactile displays	Can be used in multi-element tactile displays
Flammable	Material dependent.	Very low flammability, housing dependent	Very low flammability, housing dependent	Melts under high temperatures
Limitations	Variability of sensation, must directly contact skin, user acceptance issues	Lack of independent amplitude and frequency control	Weight, power consumption	Support equipment (valves, compressors)
Examples	EXTENSOR System by Johnson Kinetics, Inc.	TNO tactor, FOI tactor, Steadfast technologies.	C2 Tactor (Engineering Acoustics, Inc.), VWB32 (Audiological Engineering)	Steadfast Technologies PS2

* Punctateness: None: A generalized vibration with little localization, Low: Diffuse sensation with average localization, Medium: Discrete sensation, with good localization High: Point-like sensation, easily locatable, Very High: Pin prick, mildly painfully.

4.7 TACTOR CONTROL SYSTEMS

A variety of tactor control systems have been developed by various companies and organizations to drive tactors via computer or manual control. An exhaustive description of all tactor control hardware is beyond the scope of this report but the following generalized guidelines are provided. A typical tactor control system consists of 3 main components:

1) Power source;
2) A main processing unit; and
3) Tactor driver electronics.

They all usually offer the ability to control multiple tactors and allow individual or groups of tactors to be switched on and off according to some timing sequence provided by the external main processing unit (computer), or programmed on the tactor driver electronics. Depending on the type of tactor control system, the controller might also be able to control the amplitude (intensity) and frequency of the tactor.

The interface between the external main processing unit (computer) and the tactor driver electronics is typically via serial or USB bus, or special interfaces such as PC104, Bluetooth Radio or PCI bus. The output from the tactor driver to the tactor depends on the type of tactor to be driven:

- Eccentric mass/pager motors require a DC voltage in the 1.5 to 12 V range, with a current of up to 100 – 200 mA. Varying the voltage allows control of the intensity/frequency of the motors over a limited range.
- Linear actuators require an AC signal, typically a sine wave, in the 20 to 300 Hz range, with a current up to 300 mA. Frequency and amplitude (intensity) can be independently varied over a fairly wide range.
- Pneumatic tactors require an AC signal, typically a square wave, in the 20 to 50 Hz range, with a current up to 100 mA that is sent to a miniature solenoid valve assembly. Frequency can be independently varied over the stimulus range. In addition, the pneumatic tactor system needs a pressurized air source.

As electronics have become smaller, two separate architectures have emerged for tactile control systems. The first, or traditional architecture, locates all of the tactor driver electronics at one central location and uses two wires to each tactor. Newer systems (for example, TNO TACT system or the Embedded C2 system) have miniaturized the electronics and placed them at the same location as the tactor. This allows for a 2 or 3 wire bus topology to communicate to each tactor. The traditional “parallel” system is more mature and easier to implement, especially in software, but requires 2 wires per tactor. As a result, for a large array of tactors the wiring can become prohibitive. For example, a system with 112 tactors would require 224 wires from the controller to each of the elements for an individual return system or 113 wires for a common return system. The contemporary “serial” architecture demands more complex software (communication, tactor addressing), but as mentioned above, only a two or three wire bus is needed, and any number of tactors (to the maximum) can be added to the bus. As a comparison to the above given example, a 112 tactor system would require less than 30 wires allowing the architecture to be easily modified for the number of tactors.

4.8 CONCLUDING REMARKS

This chapter provided an overview of the tactile actuator technology that is currently used by NATO countries. An important fact that emerges from this overview is that the technological developments are actually quite limited and seem to be unable to keep up with the applications being developed as described in the next chapter. Simply put, there are no vibrotactile displays commercially available that suit the needs of laboratory or field testing. This results in the awkward situation that most research groups build their own systems. In line with the above, there is also a lack of standardised evaluation methods for tactile hardware, which makes it difficult to compare the different systems.

We described the four main tactor types: electro-cutaneous, rotary inertial, linear and pneumatic actuators, and their pros and cons. During the nineties the linear actuators were the most commonly used type (such as the C2 and the MiniVib). These devices were tuned to the human sensory system (see Chapters 2 and 3), for example in their frequency range to be able to address the Pacinian Corpuscles in their range of highest sensitivity (i.e., lowest threshold: 200 – 300 Hz). Interestingly, we can see that the rotary inertial tactors are getting more popular in the recent years. Experience has taught us that there is no real need (not even in operational settings) to use vibration frequencies in 200+ range, and that rotary inertial tactors

perform as well and have several advantages. One of those advantages is that there is a much larger choice in sizes, manufacturers etc. They also proved to be as robust as linear actuators. Nowadays, most labs use decade old technology that is far from perfect, but just seems to be good enough to do the job as will become clear in the next chapter on applications.

4.9 REFERENCES

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Chapter 5 – INTEGRATION ISSUES OF TACTILE DISPLAYS IN MILITARY ENVIRONMENTS

by

T. Dobbins and A. McKinley

5.1 INTRODUCTION

Tactile displays are versatile and highly valuable in a multitude of different environments, each with characteristics that substantially influence the interface with the human. As a result, a wide range of application specific phenomena must be discussed as they relate to equipment integration with the user. For example, the inertial stresses created in the high acceleration environment (measured in multiples of the acceleration due to the Earth's gravitational pull or G), water submersion, skin-tactor contact issues, vibration, and the unique features of garments and life support equipment can create factors that must be accounted for when implementing tactile technologies. These issues have been divided into their causal factors, namely those related to environmental stressors, and those dependent on the interface between the tactile equipment and the human body.

5.2 ENVIRONMENT

Among the multitude of factors that influence the successful integration of tactile displays with the human body, perhaps one of the most critical to understand is the contributions of the environmental stressors. Because tactile display applications are wide and varied including land, air, space, and sea environments, the list of potential integration issues is extensive. This section attempts to address how these major environmental stressors affect the tactile integration in the military environment.

5.2.1 Temperature

A number of experiments have shown that skin temperature has an effect on vibrotactile perception thresholds. Bolanowski and Verrillo [1] presented observers with stimuli across the frequency scale at varied skin temperatures. They found a flat response from the non-Pacinian (NP) system (< 40 Hz) from 25 to 40°C, however for the 20 and 15°C degree conditions the threshold was raised and displayed a negative slope. In a later study, Bolanowski et al. [2] repeated the temperature manipulation experiment, but included frequencies below 25 Hz. They found that temperature had an effect on thresholds at these low frequencies, especially below 12 Hz, showing a clear increase in thresholds with increased temperature at 2Hz.

5.2.2 Underwater

Verrillo et al. [3] conducted a vibrotactile threshold study in which the observer's arm was immersed in a tank of salt water. Three male subjects were tested for threshold detection of 1, 10, 100 and 250 Hz stimuli after they had been immersed in the water tank for 20 minutes. The experimenters found that there was no significant difference between the results of those conditions conducted in air and those conducted in water. However, due to the fact that water pressure increases with depth, it is possible that the tactors could become ineffective at extreme depths should the hardware reach a point where it cannot overcome the external pressure created by the water (however, please note that pressure caused by high G does not seem to have an effect; see the section below on high/variable G). In addition, this may create discomfort around the tactors themselves. Finally, it should be noted that in the underwater environment it is imperative to keep the divers' equipment simple and robust because complex equipment is more prone to

malfunction. Therefore, the decision to use complex electronic equipment underwater should be weighed carefully as it can significantly affect the results of the mission or operation. An example of underwater operations is provided in Figure 5.1.

Figure 5.1: US Navy SEAL Delivery Vehicle (SDV).

5.2.3 Whole Body Vibration

The majority of individuals experience whole-body vibration (WBV) in transport environments. The exposure of the seated or standing human to whole-body vibration can have a variety of effects on perceived comfort and health, visual acuity, speech, and hand manipulation and control. In particular, the skeletal, muscular, and visceral structure of the human body acts to amplify received vibration at frequencies between 3 and 12 Hz. Discomfort is greatest within the human resonance frequency range. Human resonance to WBV peaks at 4 – 8 Hz in the z-axis (superior/inferior) and around 1 – 2 Hz in the x (anterior-posterior) and y (lateral) axes. In the majority of military transport environments the dominant vibration is received from the z-axis.

Vibrotactile devices for orientation, navigation or messaging will be used in situations where operators will be continuously exposed to WBV e.g. helicopters, fast-jets, land vehicles, high-speed sea vessels. The majority of these platforms expose individuals to WBV between 0.1 – 80 Hz, with some significant energy within the human resonance frequency range. One group [4, 5] investigated the effect of Whole Body Vibration (WBV) exposure on vibrotactile thresholds (VT). In a series of two experiments, subjects were presented with a 1-second duration 250 Hz vibrotactile stimulus on the lateral obliques, approximately 15 cm to the right of the umbilicus. Vibrotactile thresholds were acquired using a staircase methodology. Experiment 1 was designed to investigate the manipulation of WBV amplitude; subjects

were exposed to 6 Hz WBV at 0.5, 1.5, 2.5 and 3.5m/s^2. Experiment 2 investigated the effect of the manipulation of WBV frequency and amplitude with conditions being: 0.5, 2, 12 and 16 Hz, all at 0.5, 1.5, 2.5 and 3.5m/s^2. The results of these experiments showed that the perception threshold for a 1-second 250 Hz sinusoidal VT stimulus is increased during exposure to WBV. However, the magnitude of the effect is governed by the frequency and amplitude of WBV.

5.2.4 High/Variable G

The operation of high-speed aircraft exposes the pilot and crew to high levels of G forces. Therefore the potential exists for these forces acting on the body to reduce the effectiveness of a tactile display used within the cockpit environment. Several factors exist that are capable of negatively affecting tactile perception. These include the mechanical aspects of the skin receptors, use of an anti-G suit, anti-G straining maneuvers, the overall physiological stress (including perceptual and cognitive aspects), and the mechanical function of tactors. For example, the muscle straining and respiratory activity of anti-G straining maneuvers (used to counteract the +G_z effects of reduced blood pressure and blood flow in the retina and brain) could negatively affect not only the skin receptor threshold, but also the ability to integrate tactile cues into meaningful information.

In a pilot study, Van Veen and van Erp [6] showed that vibrotactile stimulation was not substantially impaired up to +6G_z, even though wearing a pressure suit for the legs and performing straining maneuvers were part of the experimental conditions. By utilizing the Swedish Dynamic Flight Simulator (DFS), capable of accelerations up to +9G_z in closed-loop control mode, and a version of a TNO TTD for the tactile cueing, Eriksson et al. [7] investigated tactile threat cueing at increased G_z. Fighter pilots detected and intercepted threats while pulling up to +8 or 9 G_z. In addition to wearing the TNO TTD, the pilots wore their regular military underwear, anti-G suit without pressure vest, and flight boots. Anti-G straining maneuvers were performed according to regular flight procedures. The high G-stress neither critically affected the tactile vest equipment nor the human sensory system.

In addition, a study performed by Rupert and McGrath [8] tested the Tactile Situational Awareness System (TSAS) system at high G_z (up to +7 G_z) in an effort to quantify the force and frequency changes (if any) of the tactors in the high-G environment. The standard TSAS configuration consists of a vest equipped with 24 pneumatic tactors arranged in 8 columns and 3 rows. Two additional electromechanical tactors are placed on the shoulders and two more are located in the seat cushion. The pneumatic tactors are comprised of plastic bodies with latex bladders. Air is pulsed through the tactor and it is felt as a distinct tapping when placed against the body. The electro-magnetic tactors have a magnet and electrical coil and when energized produce a unique tapping sensation that “feels” different than the pneumatic tactors. The TSAS system was installed on NAMRL’s Coriolis Acceleration Platform (CAP), which is a 20 ft centrifuge capable of generating G_z levels up to 7 G_z. The various TSAS tactors were installed on a calibrated load cell that permitted measurement of the force and frequency of each type of tactor. Tactors were tested at various +G_z levels up to and including 6.5 G_z. The results of the experiment suggested that the TSAS hardware performed successfully at 6.5 G_z. The force level and frequency generated by each type of tactor were not significantly affected by G level.

As a follow-up, a high-G equipment checkout was performed on TSAS Model HT-1 utilizing the Dynamic Flight Simulator located at Wright-Patterson Air Force Base. This study was a rapid response to operational issues to validate new equipment that may warrant further testing. Of specific interest was how well different anatomical locations perceive vibration stimuli at high G_z levels. Subjects donned the standard TSAS configuration and experienced several 15-sec G_z plateaus including 5, 7 and 9G_z. Tactors were randomly excited (one at a time) and the subject was tasked with orally describing the tactor that he/she perceived. The preliminary data showed that the subjects did not have difficulty perceiving any of the tactors in any of the locations, even at 9G_z [9].

Thus, all available evidence suggests that electromechanical and pneumatic tactors function under high G_z levels, which is extremely important in fast fighter jet applications. However, it should be noted that a multitude of electromechanical tactors exist (cref Chapter 4) and only a few specific types have been studied under G_z acceleration. Hence, these results cannot be extrapolated to cover all types of electromechanical tactors. It is the opinion of the authors that most electromechanical tactors with properties similar to those presented in this section will function during high-G acceleration. Although no high-G studies have yet been performed using purely electrical shock tactors, it is expected that changes in tactile performance will be minimal given that there is no mechanical force to overcome and the electrodes themselves are extremely light-weight.

5.2.5 Space-Zero/Micro G

Van Erp et al. [10] compared reaction time (RT) to tactors worn on the torso by an astronaut in a 1G and zero G environment. Despite the overall performance gain in microgravity (i.e., faster RTs), the RTs for tactors located in the upper and lower ring on the torso were negatively affected by weightlessness: the RTs were higher than in 1 G. This indicates that, although the garment that held the tactors was custom made for the astronaut, the fit at the lower and upper rings may be improved. The optimized fit for 1G may be less optimal in microgravity due to a different posture and shifts in body fluids.

5.3 TACTOR-BODY INTEGRATION ISSUES

The tactile display will be ineffective if the tactor does not maintain contact with the operator's body. Therefore what proves effective in the laboratory and trials setting must be transferable to the operational setting. This means that the method of ensuring the tactor remains in contact must be highly reliable and not be an encumbrance or irritation to the operator. Therefore the effective integration of the tactile display system with the individual must have a high priority in the system design phase.

Beyond the environmental issues described previously, it is important to discuss the general integration issues unique to tactile displays. A thorough understanding of these key concerns is paramount to avoiding potentially serious complications that could arise from substandard display integration. For example, poor skin-tactor contact could render some or all of the tactors in the display completely useless or sporadically available at best. In turn, the display itself would become unpredictable and untrustworthy forcing it to be removed from the product or ignored. These integration issues have been described in detail in the literature. A more concise summary can be found in the following section.

5.3.1 Skin-Tactor Contact

5.3.1.1 Skin Issues

Integration issues also specifically focus on the tactor placement. The first concern is a result of varying receptor cell types and densities throughout the body. Each of the six types of receptor cells differ in rate of adaptation rate, receptive field size, sensitive frequency range, and the sensation evoked (cref Chapter 2). For example, Pacinian corpuscles create sensation of vibration/tickle whereas Ruffini endings provide sensations of stretch, shear, and tension. In addition, each of the six types of receptor cells is not uniformly distributed throughout the body. Likewise, the relative densities of each of the receptor cell types vary depending on body location. This results in the evoked sensation being dependent on the location of the tactor (stimulus).

5.3.1.2 Electromechanical Tactile Stimulation

Vos et al. [11] performed an extensive mathematical study on wave propagation in the skin and skin-tactor contact. It is expected that mechanoreceptors are best stimulated by shear waves, as shear waves exert a

local force difference on two neighbouring particles that is approximately a thousand times larger than with longitudinal waves. Consequently, shear stimulation of the skin results in more local stress in the mechanoreceptors; the receptor is stretched and compressed instead of pushed forwards and backwards when a wave passes. However, a vibrator that oscillates along the surface of the skin slips more easily than a vibrator that oscillates perpendicular to the skin. This results in a less efficient transfer of the vibration energy. Unfortunately vibration devices that are used in a tactile display often do not have a primary oscillation direction and will therefore evoke a mixture of longitudinal and shear waves with varying polarisations.

Since the epidermis skin layer is stiffer than the dermis, the vibration energy waves will propagate farther in the epidermis parallel to the surface of the skin. Shear and longitudinal waves will most likely penetrate through the dermis and the subcutaneous fat layer and reflect almost entirely on the much stiffer, underlying layer that consists of muscle or bone. The reflected waves arrive at the epidermis-air boundary under every possible angle, because of the spherical-like form of the waves. The propagation velocity of longitudinal waves in air is smaller than the velocity in skin and shear waves cannot exist in air. Therefore, only longitudinal surface waves that originate from shear waves can exist. Perpendicular excitation of the skin would of course result in a shear wave travelling along the surface of the skin starting at the rim of the source, because of the up and down motion of the skin. In the case of parallel excitation, a longitudinal wave would travel along the surface (see Figure 5.2).

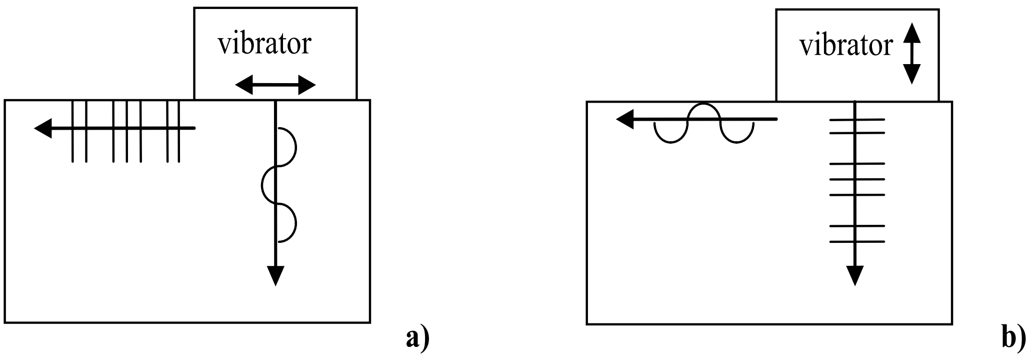

Figure 5.2: a) When the Vibrator Oscillates Horizontally, a Shear Wave Moves Downwards and a Longitudinal Wave Propagates Along the Surface. b) When the Vibrator Oscillates Vertically, a Longitudinal Wave Moves Downwards and a Shear Wave Propagates along the Surface. A combination of shear and longitudinal waves will occur at different angles.

The interface between the tactor and the skin should be designed such that the transfer of vibration energy from the tactor to the skin is large. A well designed contact will reduce the need for strong vibrators that have high energy consumption. The insertion of a material between the vibrator and the skin with the appropriate impedance will help to increase the tactor efficiency. A perfect match is not feasible in the case of longitudinal waves, because its wavelength in solid materials is meters long. For shear waves, the matching of impedances is easier. However, the impedance of the skin varies with the location on the skin so the match will never be perfect.

Another way to improve the transfer of wave energy is achieved by gluing the tactor to the skin. This will give the highest friction between the tactor and the skin. Often it will be impractical to attach the vibrator rigidly to the skin. In that case, the vibrator will be pressed onto the skin with or without a material like clothing in-between. In the first case, the vibrator should have enough static friction or else it will slip. In the latter case, it is expected that the fibres in clothes slip easily and reduce the energy transfer. With simulation, it should be possible to predict the influence of different types of clothing between the tactor and the skin.

The friction between the tactor and the skin can also be increased by applying more pressure on the tactor. However, this will stretch the skin and since it is a nonlinear material, it becomes stiffer when it is stretched. This is caused by the mechanical properties of collagen networks. In a stiffer material, there will be less attenuation of waves and a higher wave propagation velocity. Skin stretch can also occur during body movement, contact with objects in the environment, or during stimulations with large amplitudes. To keep a constant sensation, the amplitude of pressure fluctuation must be reduced. This could be accomplished by letting the force act on a large surface.

The interface between the tactor and the skin also plays a role in localising the vibrations in the skin; all waves will attenuate with the distance from the source. When the contact area between the vibration source and the skin is large, the waves will behave more like plane waves. When it is small, the wave will behave more like spherical waves. Consequently, vibrations originating from a small contact area will dampen more quickly than waves originating from a large contact area. A small contact area is preferable, since it reduces the spreading of the vibrations. It also reduces the need for strong vibrators, because less skin mass has to be moved.

A vibrator can be isolated from its carrier by embedding it in a soft material with an impedance that greatly differs from the impedance of the vibrator, which in turn is surrounded by another dense material. This second layer causes the vibration to be reflected back to the source. Care should be taken that vibrations do not leak to the bulk material via the skin. Fixation of the skin just around the vibrator will damp the waves travelling on and near the surface of the skin, but not the waves deeper below the surface.

5.3.2 Electrical Tactile Stimulation

Perhaps one of the most critical concerns with tactile displays involves the perception of the tactor when it is energized. Human observation of each individual tactor is only possible when the tactor is in contact with a part of the body or skin. This consideration is certainly most prevalent in purely electrical tactor systems due to the fact that each electrode (tactor) must be in *direct* contact with the skin to produce a perceptible stimulation. Because the excitation of the skin receptor cells is performed by delivering electrical current directly to the skin, several integration issues arise. First, the impedance between the skin and the tactor electrode must remain low. Dry skin/tactors yield very high impedance that tends to produce an uncomfortable "prickly" sensation. It is believed that this is a direct result of the inconsistent current distribution within the skin-tactor interface. Hence, an electrolytic solution should be applied to each of the tactors prior to use. However, it should be noted that generally subjects develop a layer of sweat under each of the tactors (electrodes) after a few minutes of wearing the garment. The sweat has been informally shown to provide an acceptable substitute for the electrolyte solution. Nevertheless, long term changes in impedance have not yet been investigated without the use of a manufactured solution (e.g., saline solution). Finally, securing the electrode wires and incorporating the tactors into appropriate garments in an unobtrusive manner remains a challenge.

5.4 HARDWARE ISSUES

The final set of concerns deal with the tactile display hardware integration with the operator.

5.4.1 Weight

The development of 'future soldier systems' is anticipated to increase the mass of the equipment carried by the operator. The addition of a multi-tactor system has the potential to add to this mass burden by the inclusion of tactors, a driver system and a power supply. If the tactile display has a minimum number of tactors then this may not be an issue, whereas a multi tactor system (e.g., 64 tactors) may have a significant weight penalty. This may serve only to further compromise the effectiveness of the individual

by reducing mobility, increasing physical workload, and adding bulky items that are capable of being snagged on obstacles and building features. It is likely that future developments in power supply and tactor technology will significantly reduce the weight of the systems and make portable, high-resolution tactile systems relatively easy to implement on the dismounted soldier.

5.4.2 Equipment Ditching

Many operations require that an operator's equipment can be quickly removed to ensure safety. This requires that the wiring system for the tactile display must not inhibit the removal of the personal equipment. Therefore designers will be required to identify whether wireless links or quick-disconnect connectors are more appropriate in the systems' design.

5.4.3 Emergency Egress

For the same safety and mission effectiveness reasons that specify personal equipment must be easily removable, personnel must also be able to evacuate their vehicle or workstation in a minimum time frame. This again means that the systems designer must include quick disconnect connectors or wireless links where appropriate. For example, helicopter pilots should not need to physically disconnect the tactile display electrical connections from the aircraft in order to egress in emergency situations. The device should operate via wireless connections or the connector should automatically disconnect when moderate tension is applied.

5.4.4 Comfort

Comfort is an essential part of clothing and equipment that is worn by an individual. If the operator is uncomfortable they are unlikely to use the tactile display and thus its potential advantages will not be realized. This issue is discussed in more detail by van Erp [12].

5.5 CONCLUDING REMARKS

Chapters 2 and 3 discussed the physiology and the human factors issues related to tactile displays. These issues must be considered when attempting to integrate laboratory-based system in actual military environments. A robust system must be able to withstand a myriad of environmental stressors, which may include vibration, large variations in temperature, underwater submersion, sustained accelerations, impacts and microgravity. The tactile display must be integrated with the current military garments, which may cause challenges in skin-tactor contact, weight, ditching, emergency egress, and comfort. Although these integration issues are complex, there have been many successful applications of tactile displays. A number of these will be discussed in Chapter 6.

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Chapter 6 – APPLIED RESEARCH REVIEW/LESSONS LEARNED

by

W. Ercoline and A. McKinley

6.1 INTRODUCTION

This chapter briefly summarizes past and current applied research with an emphasis on lessons learned. It is not intended to cover the entire database of published research articles. The taxonomy for this chapter organizes the information into the four basic topics of Air, Land, Sea, and Other.

6.2 AIR

The intricate dynamics and high speed of the modern manned flight environment can provide conflicting cues to the pilot's vestibular system regarding his/her true position in reference to the ground in the absence of out-the-window visual cues. These conflicts are often referred to as spatial disorientation and have contributed to many mishaps (see Chapter 1). Often these illusions are most prominent when the accelerations of the aircraft occur below the threshold of perception of the pilot. Tactile displays provide a method of providing orientation cues during such instances thereby mitigating the debilitating effects of the illusion. Additionally, tactile cues may be used to provide targeting location, which may reduce demands on the visual system [1].

6.2.1 Fixed-Wing Manned Aircraft

6.2.1.1 Self-Motion During Spatial Disorientation [2]

Summary: van Erp et al. investigated the effectiveness of a tactile torso display as a countermeasure to spatial disorientation (SD), and whether the display should follow an inside-out or an outside-in coding. Twenty-four subjects participated, 12 in each coding group, matched for age and gender. The researchers used a rotating chair to induce SD by spinning subjects about their yaw axis followed by a sudden stop. During the ensuing recovery phase, a random disturbance signal was added to the chair's orientation. Subjects actively controlled their orientation and were instructed to maintain a stable orientation. Statistical analyses revealed that recovery from SD was improved with support of the tactile instrument ($p < .001$, mean number of spins reduced from 8 to less than 1), but that tracking performance was reduced ($p < .001$, mean correlation between error and control signal reduced from –.87 to –.80). The effects were the same whether the instrument was available full time or during the recovery phase only. There were no differences between outside-in and inside-out coding. The present study demonstrates the potential of tactile cockpit instruments in limiting SD, even in the presence of strong, but misleading self-motion information from the vestibular sense.

Lessons Learned: There appears to be no apparent difference in performance utilizing outside-in or inside-out tactile symbology. Evidence suggests that the subject performs equally well with either method of coding given that the proper training has been accomplished. It is also important to note that prior experience may influence the preference of the individual. Hence, prior experience with inside-out visual displays may yield a greater preference for inside-out tactile displays.

6.2.1.2 T-34 Tactile Situational Awareness System (TSAS) Project

The T-34 TSAS project integrated a tactile display into a T-34 aircraft [3, 4]. A 7-event test operation was conducted to demonstrate that a pilot could maintain aircraft orientation using a tactile display during

flying operations. One United States Navy (USN) test pilot was selected to fly the flight events. Objectives of the T-34 TSAS flight demonstration (see Figure 6.1) program were to show:

- That a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch; and
- The use of the TSAS display to show that a pilot, with *no visual cues*, can effectively maintain effective control of the aircraft in normal and acrobatic flight conditions.

Figure 6.1: A T-34 Equipped with a Tactile Situation Awareness System during a Flight Demonstration Project.

Summary results showed that roll and pitch tactile cues could be provided via a matrix array of vibrotactors incorporated into a Tactor Locator System (TLS), a variant of the TSAS. The TLS was a torso harness of cotton and fire retardant NOMEX with elastic and velcro straps that was worn underneath the flight suit. The TLS positioned the 20 electro-mechanical tactors on the torso as an array of 4 columns of 5 tactors located 90 degrees apart on the front, left, back, and right of the test pilot. The test pilot in the rear seat was shrouded to block any outside visual cues and all flight instruments in the rear cockpit were removed. The test pilot flew the following maneuvers: straight and level for 5 minutes; climbing and descending turns; unusual attitude recovery; loops; aileron rolls; and ground controlled approaches (GCA). The test pilot successfully performed all maneuvers without visual cues, relying solely on tactile cues for attitude information.

For this flight demonstration, two different “tactile pages” were developed using variations of tactor stimulus selected from intensity and location. The first tactor page was used for fine control of the aircraft, and the second program was used for acrobatic control. The first or “fine” page had a pitch and roll range of +/- 40 degrees and used only 3 tactors per column, while the second or “acrobatic” page had a pitch and roll range of +/- 180 degrees and used 5 tactors per column. Flight performance showed that it was more intuitive and easier to distinguish between a low, middle and high tactor. As a result, during non-acrobatic maneuvers, improved performance was noted using the fine page as compared to using the 5 tactor acrobatic page. Only the acrobatic control program could be used for the acrobatic maneuvers. These results indicate that the tactile display should provide information optimized for a particular flight regime, and that the test pilot could distinguish between fine and acrobatic tactor “pages”.

Lessons Learned: This flight demonstration provided evidence that tactile displays can be utilized to intuitively provide orientation information through the somatic modality. It also demonstrated that the information provided through the tactile display allows the pilot to maintain control of the aircraft during both straight and complex maneuvers with no visual cues. However, as the flight demonstration utilized a limited number of pilots and aircraft, further investigation is warranted to ensure the intuitiveness of the

tactile displays across a general pilot population. In addition, the use of TSAS in aircraft with higher performance characteristics should be assessed.

6.2.2 Rotary-Wing Manned Aircraft

6.2.2.1 Cockpit Instrument to Support Altitude Control [5]

Summary: van Erp et al. tested the effect of a tactile torso display on maintaining an instructed altitude during low level flight. The tactile instrument consisted of 64 vibrating elements attached to the torso, shoulders and thighs of the pilot. In a helicopter simulator, 12 student pilots flew under different visual (full vision and night vision) and tactile conditions (none, a simple version, and a complex version). The simple version of the tactile display presented the direction of the desired altitude. The complex version added the current motion direction. The participants performed an additional cognitive task during half of each scenario. Performance and subjective mental effort ratings were analyzed. The results showed that the tactile instrument halved the altitude error without affecting the mental effort rating. This effect was present in full vision and in night vision conditions. There were no differences between the two versions of the tactile instrument. The authors concluded that this emerging technology is a powerful support in a low-level flight without increasing the pilot's mental workload.

Lessons Learned: This study provides evidence that tactile displays can be used in both simplistic and complex fashions to display information to a pilot without significantly increasing mental workload. In addition, the tactile modality can serve as a vehicle for sending additional information to increase the situational awareness of the pilot. This was evidenced by the significant performance improvements.

6.2.2.2 Tactile Display and Night Vision Goggles [6]

Summary: The degraded visual information when hovering with Night Vision Goggles may induce drift that is not noticed by the pilot. Researchers at TNO tested the possibility of counteracting these effects by using a tactile torso display. The display consisted of 64 vibro-tactile elements and presented information on the desired direction of motion (simple version), and also information on the current motion direction (complex version). The participants flew in a fixed-base helicopter simulator with either full vision or simulated night vision goggles. The results showed performance improvement for both tactile display variants compared to hovering without a tactile display. This improvement was present in the NVG conditions (mean reduction of the position error of 22% in the horizontal direction and of 41% in the vertical direction), and also in the full vision condition (mean reductions of 32 and 63%, respectively). Additionally, performance with a tactile display was less affected by the introduction of a secondary (cognitive) task than performance without a tactile display. The complex variant of the tactile torso display tended to be less effective than the simple variant. It is hypothesized that this effect may be due to "*tactile clutter*". This simulator study proves the potential of intuitive tactile torso displays in reducing drift during hover.

Lessons Learned: The evidence provided by this study indicates that information can be effectively communicated through surrogate sensory modalities (e.g., tactile) without increasing attentional or cognitive demands. Provided with a simple, intuitive tactile display, subjects can maintain helicopter hover, regardless of the prevalence and salience of the visual cues. However, the issue of "tactile clutter" can nullify or attenuate the benefits of the tactile display; thus the design and implementation of the system become critical considerations.

6.2.2.3 The Role of Intelligent Software in Spatial Awareness Displays [7]

Summary: This series of flight demonstrations was aimed at assessing the Tactile Situation Awareness System (TSAS) in a variety of aircraft and situations. Specifically, TSAS was utilized in an effort to

provide aircraft state information to the pilot and reduce their visual workload; its usefulness in the absence of visual cues was also assessed.

6.2.2.3.1 UH-60 TSAS Programme

The UH-60 TSAS flight demonstration project was a follow-on effort to the fixed-wing T-34 TSAS flight demonstration and integrated the tactile display into a UH-60 helicopter. A 9-event test operation was conducted to demonstrate that a rotary wing pilot could receive aircraft orientation and performance information using a tactile display during flying operations. Three US Army (USA) pilots were selected to perform the flight events. Objectives of the UH-60 TSAS flight demonstration program were to demonstrate:

- That a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch; and
- The use of the TSAS display to show that a pilot, with *no visual cues*, can effectively maintain control of a helicopter in the complex rotary wing environment.

The flight demonstrations showed that controlled flight maneuvers in a rotary wing aircraft using tactile information were possible. Roll and pitch tactile cues were provided via a matrix array of vibrotactors incorporated into a torso harness as used for the T-34 effort. Additionally, airspeed and heading error tactile cues were provided by tactors located on the arms and legs, respectively. The blindfolded test pilot in the right seat had no visual cues. The test pilots flew the following maneuvers: straight and level; standard rate turns; unusual attitude recovery and ground controlled approaches. The test pilots were able to successfully perform all maneuvers without visual cues, relying solely on tactile cues for the necessary attitude and performance information.

The auxiliary tactile cues from the torso caused some difficulties. Heading control remained problematic during the demonstration as pilots had some difficulties picking up the heading error signal when the other pitch and roll channels were active. This suggests that keeping the heading tactors off until the pilot approached straight and level flight would improve the ability to return to a base course following unusual attitude recovery.

Lessons Learned: This follow-on flight test illustrated the potential for utilizing tactile displays in rotary-wing applications. Available evidence indicates that the tactile cues can be sensed despite the high-vibration environment created by the revolving rotors. In addition, it was learned that providing multiple cues simultaneously can become problematic due to the fact that the stimuli were similar. This presents a recondite situation where tactile cues may overlap and provide rather confusing signals. A better approach may be to provide only one type of information at a time depending on the needs of the pilot.

6.2.2.3.2 JSF / UH-60 TSAS Programme

The Joint Strike Fighter (JSF)/UH-60 Tactile Situation Awareness System (TSAS) flight demonstration project [8] was a short-duration technology maturation and flight demonstration program funded by the JSF Program Office. The JSF-TSAS project integrated a tactile display, F-22 cooling vest, and GPS/INS technologies into a UH-60 Helicopter (Figure 6.2). A 10-event test operation was conducted to demonstrate the utility of this advanced human-machine interface for performing hover operations. Four test pilots were selected to perform the flight events.

Figure 6.2: TSAS Equipped UH-60.

Objectives of the JSF-TSAS flight demonstration program were to demonstrate:

- The potential for TSAS technology to reduce pilot workload and enhance situation awareness (SA) during hover and transition to forward flight; and
- The use of the TSAS display to show that pilots, with no outside visual cues, can effectively hover and transition to forward flight in a vertical lift aircraft.

Summary results showed that TSAS technologies increase pilot SA and reduce pilot workload when using the tactile display, especially during simulated shipboard operations in Instrument Meteorological Conditions (IMC). Prototype hardware development showed that tactile display could be integrated into existing flight gear (Figure 6.3). The test pilots successfully performed all maneuvers with degraded outside visual cues, relying on tactile cues for the necessary information. Using TSAS, pilots demonstrated improved control of aircraft during complex flight conditions. The tactile display reduced pilot workload and provided the opportunity to devote more time to other instruments and systems when flying in task saturated conditions. These effects can potentially increase mission effectiveness. One US Army test pilot commented that “in IMC, the TSAS vest could be the difference between mission success and a mishap.”

Figure 6.3: TSAS Experiment Pilot Showing TSAS Tactor Locator System.

The awareness of aircraft velocity over the ground or “drift” without looking at a visual instrument was the biggest advantage of the JSF-TSAS. The maintenance of SA during hovering in reduced visual conditions was enhanced. Overall, TSAS decreased pilot workload and enhanced SA.

Lessons Learned: The TSAS flight tests were able to demonstrate that a pilot can maintain control of an aircraft using tactile cues and that a tactile display can reduce workload and enhance SA. However, the following issues need to be addressed:

- *The need for improved tactors*. The prototype tactors used in the flight demonstrations could only be turned on and off. The amplitude, frequency, and stimulus type (vibration, stroking) could not be controlled in the prototype system. This is analogous to a black and white vs. a color visual display. A "richer" tactile sensation that could convey compound information can be achieved with improved tactors.
- *Incorporating the absolute minimum number of tactors into existing flight gear*. Today's aviator is asked to wear an ever-increasing amount of equipment. A tactile display that has a minimum number of tactors while still providing the necessary information will be lighter, more robust, and easier to maintain than a tactile display with a large number of tactors.
- *Keeping the tactile display intuitive and easy to understand.* If the user must spend extra time cognitively processing the displays, then many of the advantages of using this modality is lost. It is also important to avoid tactile clutter and overly complex tactile coding.

6.2.2.4 Canadian Helicopter Test [9, 10]

Summary: This study investigated the effectiveness of the Tactile Situational Awareness System (TSAS) in maintaining position during a high hover maneuver and a simulated shipboard-landing maneuver in both good and degraded visual environments (see Figure 6.4). Objective flight performance and subjective evaluation of situational awareness (SA), workload and self-performance evaluation were measured. Results show that providing a combination of position and velocity signals enhanced pilot performance, eliminated low frequency drift problems, improved situational awareness, and did not increase pilot workload. In general, information based on tactile cueing is effective in reducing hover position error in the axis where the cues are presented. During high hover in degraded visual environments, the use of TSAS cues resulted in performance improvements of 59% in horizontal positioning accuracy and 67% in vertical positioning accuracy. During shipboard landing maneuvers, pilot performance was significantly better with TSAS than without TSAS. Furthermore, the provision of horizontal information via the TSAS appeared to enhance performance in the vertical axis as well. The mechanisms leading to this improvement demand further investigation.

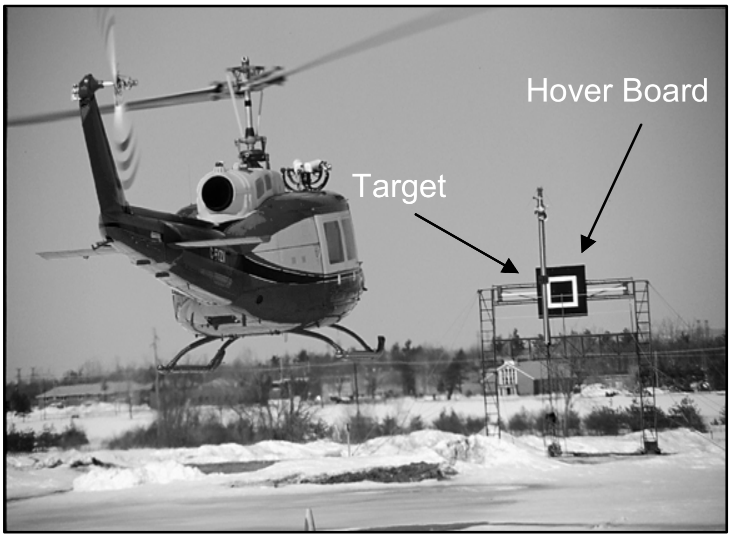

Figure 6.4: TSAS Equipped Helicopter Performing Hover Task.

The TSAS is a valuable and effective tool in improving pilot performance during precision hover maneuvers and during visually saturated tasks, particularly during degraded visual environments. With minimal training, pilots were able to reduce their RMS position error in horizontal, vertical, and lateral axes, depending on the maneuver. This performance improvement was accompanied by a concurrent improvement in subjective situational awareness ratings and subjective performance ratings. A corresponding increase in subjective workload rating is notably absent.

Aircrew members unanimously agreed TSAS was effective, reduced workload, and improved SA. One of the most promising uses for TSAS involves missile warning/tracking cues combined with terrain following (TF) climb/dive inputs. The TSAS vest provided excellent threat SA to the crew by using variable frequency directional inputs. Combined with vertical cueing from the TF radar, missile warning cues gave the crew SA on the threat as well as terrain awareness.

Lesson Learned: The TSAS improves aircrew SA, reduces aircrew workload, and demonstrates potential suitability for the Air Force Special Operations Command (AFSOC) mission. The prototype TSAS, in its conception phase, is not operationally suitable for the AFSOC mission. However, with further refinement and continued testing, it can become an effective aircrew aid during critical phases of flight. Quantitative data recorded during flight and simulator sessions showed hover performance, measured as drift velocity, improved with TSAS usage.

6.2.3 Unmanned Aerial Vehicles

As the Air Force moves toward the future there will be a greater utilization of unmanned aerial vehicles (UAVs) to support the full spectrum of missions. Pilots of UAVs are faced with the difficult task of controlling the aircraft from a remote ground control station. Feedback from the UAV operating station is vital for pilots to effectively control the UAV. Many current UAV ground control stations include a monitor that shows the pilot a map and a second monitor that displays a nose camera view combined with a heads-up display (HUD). Since operators control the UAV from a ground control station that is remote from the actual aircraft, the pilot is not provided with the normal auditory, vestibular, and proprioceptive feedback they would receive in the actual aircraft. There is a larger mishap occurrence in UAVs than in manned aircraft, which may be in part due to the “out of cockpit” experience while piloting them. UAVs have on average 141 mishaps per 100,000 flight hours, while manned aircraft have one mishap per 100,000 flight hours. Twenty-two percent of these mishaps occur during the landing phase of UAV operation [11]. Tactile feedback may be a method to reduce the demand on a UAV pilot’s visual load and provide the kind of feedback needed to effectively operate the UAV in all phases of its mission.

6.2.3.1 Effect of Tactile Feedback on Unmanned Aerial Vehicle Landings [12]

The purpose of this study was to assess the potential for a vibrotactile vest to provide tactile feedback to UAV pilots during landing. All tests were performed on a UAV synthetic task environment (STE) simulator, which is derived from the Predator workstation. Thirty participants were recruited from United States Air Force Academy cadets in an upper-division leadership class. The subjects were divided into two groups of fifteen. The first group used the UAV simulator as it is currently employed with no tactile vest. The second group used the UAV simulator while also using the tactile vest. The learning performance of each group was examined by measuring the number of trials required to obtain a passing landing score for the initial condition each participant is assigned. After obtaining a passing score, the participant switched to the other condition (vest or no vest) and completed an additional three trials. The root mean square (RMS) error from an optimal flight path was used to analyze the impact of initial training with and without the tactile vest. The results are displayed in Table 6.1 below.

Table 6.1: Overall Performance Results of Participants by Condition (Mean ± SD)

	Vest	No Vest
# of Trials to Obtain Passing Score	3.53 ± 1.41[a]	7.13 ± 2.72[b]
Glideslope RMS Error	38.57 ± 12.18[a]	54.53 ± 23.82[b]
Post-trial Glideslope RMS Error (three trials)	31.04 ± 10.40[b]	25.82 ± 10.49[a]

[a]Group 2: Wore vest first, then no vest [b]Group 1: No vest first, then vest.

Lessons Learned: The performance of the vest condition significantly outperformed that of the no-vest condition in number of trials until the landing task was successfully completed. This supports the possibility that tactile feedback can be used in training novice pilots to fly UAVs, and that tactile cues may be useful for operational UAV pilots.

6.3 LAND

Soldiers have specific and sometimes unique requirements for operation and often operate in extremely demanding physical environments. Information systems may demand visual attention and can occupy the soldier's hands to carry the display. Soldiers may therefore be particularly interested in the hands-free, eyes-free, and mind-free aspects of tactile displays. This allows them to move with their weapon at the ready and with their eyes and attention focused on terrain and enemy threats. Soldiers in tanks or other ground moving vehicles must often operate in extreme noise and high vibration and also need to focus their visual attention on the outside world. Here also, tactile displays may improve information transfer.

6.3.1 Navigation [13]

Summary: Presenting waypoint navigation on a visual display is not suited for all situations. The present experiments investigate if it is feasible to present navigation information on a tactile display. An important design issue of the display is how direction and distance information must be coded. Important usability issues are the resolution of the display and its usefulness in vibrating environments. In a pilot study with 12 pedestrians, different distance-coding schemes were compared. The schemes translated distance to vibration rhythm while the direction was translated into vibration location. The display consisted of eight tactors around the user's waist.

Lessons Learned: The results show that mapping waypoint direction on the location of vibration is an effective coding scheme that requires no training, but that coding for distance does not improve performance compared to the control condition with no distance information.

6.3.2 Vehicle Navigation [14]

Summary: A vibrotactile display, consisting of eight tactors mounted in a driver's seat, was tested in a driving simulator. Participants drove with visual, tactile and multimodal navigation displays through a built-up area. The time to react to navigation messages and the workload were measured for normal and high workload conditions. The results demonstrated that the tactile navigation display reduces the driver's workload compared to the visual display, particularly in the high workload group. The fastest reaction was found with the multimodal display.

Lessons Learned: This study quantitatively supports the claims that a localized vibration or tap is an intuitive way to present direction information, and that employing the tactile channel may release other heavily loaded sensory channels, therefore potentially providing a major safety enhancement.

6.3.3 Land Navigation [15]

Summary: TNO Netherlands developed a wearable system to allow land waypoint navigation, designated as the Personal Tactile Navigation system (PTN) [16]. Eight tactors are equally spaced on a torso belt connected to a digital compass and GPS system. Waypoints can be programmed into the system and the wearer is then guided to each of these positions through tactor-based guidance. This provides the individual with critical directional information without having to consult the usual visual-based navigation systems (e.g., compass, GPS devices). The PTN was evaluated, along with other navigation systems, by US Army Infantry soldiers in a collaborative effort between TNO Netherlands and the US Army Research Laboratory [17]. Other systems included traditional map and compass, the current operational Army GPS device (analogue display), and the prototype head-mounted map display in the Army Land Warrior system. Experimental field evaluations in operationally realistic and demanding multi-task scenarios enabled assessment of each navigation system for many performance indices, including waypoint achievement, navigation time, deviation from route, avoidance of terrain obstacles, and avoidance of off-limits areas. Performance on secondary tasks such as response to radio communications and detection of targets was also assessed, and soldier-based evaluations were collected. Soldiers achieved 100% of the waypoints with the PTN in daytime and also in night operations, and tended to detect more targets and/or move more quickly.

Lessons Learned: Soldiers indicated high levels of approval for the PTN system, particularly for aspects such as ease of use. The majority of soldiers preferred the PTN system first, and the head-mounted visual map display second. The head-mounted visual map display was rated higher than other systems for providing location information. Comments emphasized that the PTN system was “hands-free, eyes-free, and mind-free,” thus freeing the soldier to move with their weapon at the ready with their attention focused on terrain and enemy threats.

6.3.4 Army Platoon Leader Decision Making [16 – 18]

Summary: This study investigated effects of visual, audio, and tactile alerts on command decision-making of a Platoon Leader (PL) during a computer-based simulation of a mounted attack mission. An Army infantry command and control research platform (AEDGE- Agent Enabled Decision Group Environment) presented each PL with three equivalent scenarios. In one condition, cues regarding level of importance of incoming information and direction of threat were presented through a visual icon (red flashing symbol). In the second and third conditions, cues were audio (beeping noise) and tactile (arm-mounted tactors), respectively. Multi-modal conditions (visual and audio; visual and tactile) were also investigated.

Lesson Learned: Results indicated that audio and tactile cues were more effective than visual cues, particularly in reducing time to respond; the PLs could be alerted effectively without having to constantly monitor the screen for visual alerts. PLs reported that tactile cues were less annoying and therefore more manageable.

6.3.5 Tactile Support of Shooting Performance in Computer-Based Army Simulation [16 – 19]

Summary: This study investigated effects of tactile, visual, and auditory cues about threat location on target acquisition and attention to visual and auditory communications. Army soldiers participated in computer-based shooting simulations, where the task was to search and shoot hostile targets on the

computer screen. Alerts were provided in the form of visual icon (clock display) that matched the targeting control dial, spatial language (audio speech indicated by "target at one o'clock", etc.), and 3D audio and tactile alerts from tactors on a torso belt. All cues provided location information on each target. The visual icon produced the fastest and most accurate response.

Lessons Learned: The favourable result for the visual display may be due to congruence between icon and task (e.g., the shooter is always looking at the screen, and the icon is thus easy to see). Also, in the test setup used, there was no visual load; soldiers were allowed to look at the visual display and had no other visual task than to detect the target.

6.3.6 Auditory and Tactile Threat Cueing in Combat Vehicle 90 [20, 21]

Summary: This experiment investigated the performance of 3D audio and vibrotactile technologies to indicate horizontal directions of threats to the driver of the light armored tank Combat Vehicle 90 (CV 90) Technology Demonstrator. Delivered by the warning and countermeasure system (WCS) with an in-vehicle PC connection, threat cueing was made by either 3D audio sound in headphones or tactile vibration from a single-row of 12 tactors onto the torso, or both in combination. Ten male CV 90 drivers from the Swedish Army Combat School participated in the task, which was to determine the direction of each threat and then turn the vehicle toward it as quickly and accurately as possible. Compared with the auditory and visual threat cueing currently employed, the 3D audio and vibrotactile technologies were considered superior for immediate detection of horizontal threat directions. The drivers had an excellent overall performance in reacting to and positioning the vehicle toward threats. It was noted that the 3D audio used needs improvement with regard to front-back confusion if it is not combined with tactile cueing.

Lessons Learned: Employing 3D audio and tactile cueing could enhance the utility of not only the individually functioning CV 90 WCS but also the WCS network for a unit of CV 90s.

6.3.7 Ground Navigation Tests [22]

Summary: During ground tests, a 5-minute, 1.6 mile, 3-leg course was mapped. Each subject navigated the course using the TSAS-Special Forces (TSAS-SF) tactile display, and then using the visual display on the GPS. For this preliminary investigation, no attempt was made to minimize order effects. For additional visual tasking, a number of small objects (10 green and 10 black) were placed along the route. A count of the number of objects of each color observed on each run was taken. Preliminary data collected showed that the number of objects correctly identified was higher with TSAS-SF than with visual displays.

Lessons Learned: Preliminary results, both qualitative and quantitative, suggest that the use of the TSAS-SF for ground navigation allows the subject more "heads up" time. This "heads up" capability can improve search capability of both hostile and friendly factors. When combined with an additional visual task, tactile cues show the potential to be an effective alternative or enhancement to visual displays. The majority of subjects felt that TSAS was easier to use, provided enhanced navigation, and was preferred over the visual only display. This would be invaluable to Special Forces operators in increasing mission effectiveness.

6.4 MARITIME

The tactile display has the potential to enhance maritime operational effectiveness and safety. A number of trials have been successfully undertaken either in the maritime environment, or are such that they can be directly related to the marine environment. Many of these were highlighted by Dobbins and Samways [23] at the NATO RTO symposium on spatial disorientation. These have primarily been designed for

navigation/orientation cues, although other specific applications have been identified. The following sections highlight the results of maritime related trials, and recommend where future development work may be focused to enhance performance and safety.

6.4.1 Surface Operations

The advent of GPS navigation technology has dramatically improved the ability to navigate successfully at sea. Such systems now provide the capability to develop tactile display systems that can enhance the performance and safety of the coxswain and their craft. Navigation in poor visibility (e.g., in fog and at night) is dangerous and can be exceptionally hazardous when operating in poor sea conditions where the craft have to maneuver through large waves/swell. In these poor weather conditions, the coxswain's attention needs to be focused on multiple information sources: the sea, the required heading, the craft/engine condition, operational/tactical information, and audio communications. The tactile display has the ability to intuitively display the required craft heading while allowing the coxswain to pilot the craft safely around waves and obstacles, and attend to other tasks such as audio communications.

There are a number of examples of successful tactile navigation/orientation. These often use different methodologies to display the direction of travel or a correction to a course travelled. These display methodologies have advantages and disadvantages depending on the specific application.

6.4.1.1 The Use of a Navigation Tactile Interface System in Establishing the Blind World Water Speed Record [24]

Summary: The QinetiQ Centre for Human Sciences developed a Navigation Tactile Interface System (NTIS) that displays navigation cues through the highly intuitive sense of touch. The system was used to assist in establishing a blind world water speed record. The NTIS allowed the boat to be autonomously navigated by the blind driver between pre-determined waypoints with minimal input from a sighted passenger. The display was designed to operate as a virtual corridor so as to minimise course errors. This resulted in continual feedback to the driver and provided the ability to navigate a straight line course at high speed with no visual cues. As a result, a world record speed of 73 mph was established, which was ½ mph less than the sighted record for the make of boat used.

Lesson Learned: Navigation cues were successfully delivered to allow a blind person to drive a boat at high speed between predetermined positions. This suggests that tactile displays can provide craft heading cues to boat drivers in poor visibility conditions and at night.

6.4.1.2 The Use of Tactile Navigation Cues in High-Speed Craft Operations [25, 26]

Summary: Currently three methods of displaying directional cues have been successfully demonstrated on high speed craft. The first two are based on a two tactor system with the tactors placed on the arms, hands or torso and display a virtual corridor or a direction to the selected waypoint (refer to Figure 6.5 for a graphical representation of the systems effectiveness). This system demonstrated mean cross-track-error values of < 0.12 $\%.km^{-1}$ of the distance traveled between way-points. The third method uses a multiple tactor system where the tactors are placed in a ring around the torso [26] to provide an indication of the direction of the selected waypoint.

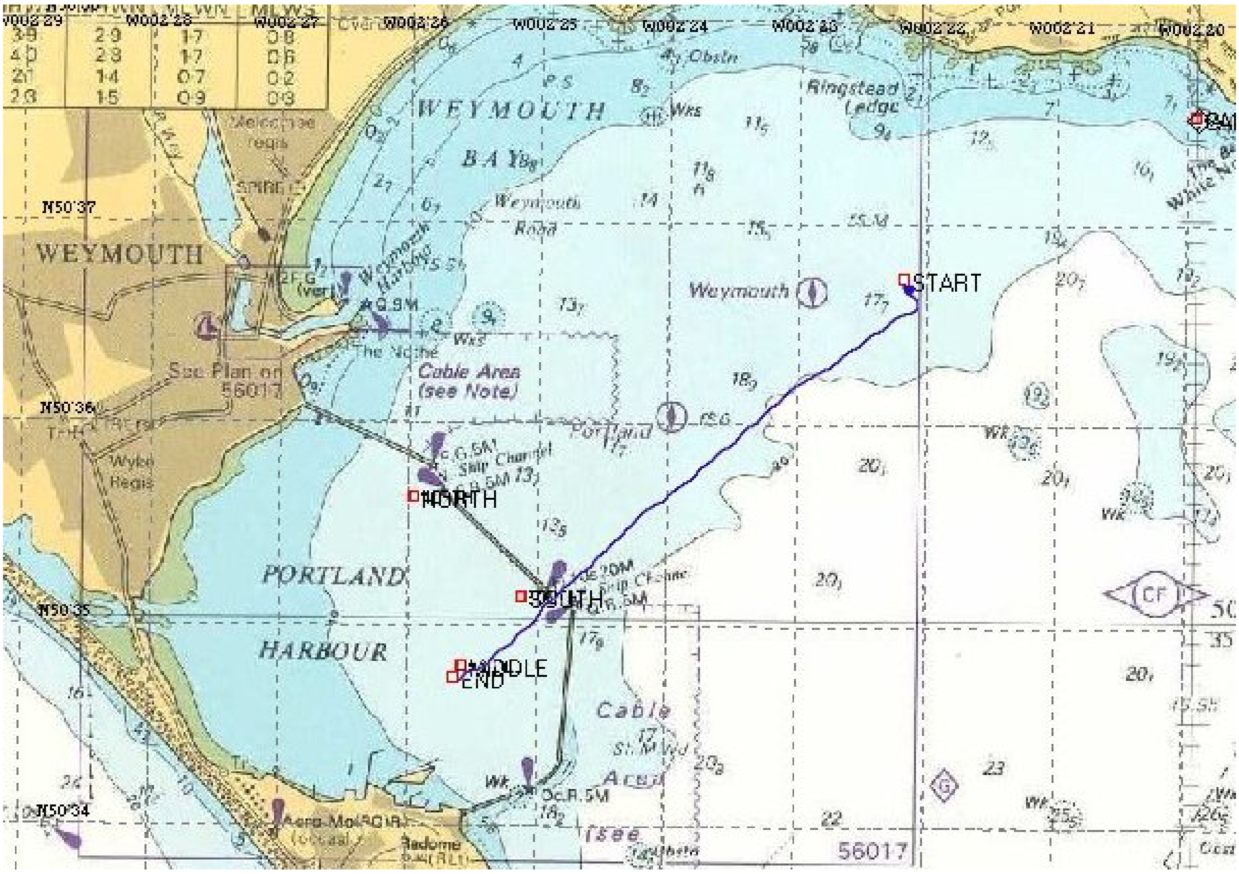

Figure 6.5: Example of Navigation Track Using a Tactile Navigation System Based on a Two Tactor Display.

Anecdotal feedback from experienced high speed craft coxswains has indicated that these tactile displays have the potential to provide intuitive direction cues. These methods of providing craft heading cues may be advantageous when the coxswain has a high cognitive workload in poor environmental conditions (e.g., elevated sea-states, poor visibility and at night). The use of the tactile display allows them to concentrate their attention on the sea and therefore not have to continually look down to obtain directional cues from a compass or chart plotter.

Lessons Learned: Tactile navigation displays have the potential to enhance both situational awareness and safety in high-speed craft operations by reducing operator workload and by providing intuitive navigation cues in adverse weather conditions.

6.4.2 Diving Operations

Humans operate in the underwater environment either as free swimming divers, submersible operators, or as Unmanned Underwater Vehicle (UUV) operators. All of these roles can result in the operator having limited situational awareness, and expose them to the risk of spatial disorientation.

The diver(s) responsible for the safe operation and navigation of small submersible vehicles (e.g., the US Navy SEAL Delivery Vehicle (SDV), refer to Figure 5.1) have to maintain an effective level of situational awareness and spatial orientation. This is achieved through the use of computerised sensor systems. Tactile displays offer an effective solution to maintaining and enhancing the performance (i.e., navigational accuracy and obstacle avoidance) of the vehicle.

It should be noted that in the underwater environment it is imperative to keep the divers equipment simple and robust because if the equipment can break – it will break. Therefore the decision to use complex electronic equipment underwater should not be taken lightly.

6.4.2.1 Enhanced Situation Awareness in Sea, Air, and Land Environments [22]

Summary: In the last few years divers have had the opportunity to utilise computerised navigation and sensor systems. As well as providing the diver with enhanced situational awareness, it has also provided the opportunity to overload the diver with information, therefore potentially compromising their performance. To determine the feasibility of using tactile navigation in an underwater environment in an attempt to offload the visual channel, a test was conducted with the Very Shallow Water (VSW) Mine Counter Measure (MCM) unit. A similar unit is displayed in Figure 6.6. Divers conducting VSW MCM operations navigated using the Swimmer Inshore Navigation System (SINS) while simultaneously monitoring mine detection sensor displays. TSAS was integrated into the SINS to provide underwater tactile navigation data. The subjects navigated a triangular course and navigation cues were provided visually via the SINS display or via tactors attached to the divers' wrists. The results demonstrated that tactile cues, utilising a virtual corridor concept, can be used to provide effective directional instructions to underwater divers and submersible operators.

Figure 6.6: The QinetiQ Driver Reconnaissance System (DRS) with the Display Screen Showing a Sonar Image.

Lesson Learned: Results of the underwater tests and subjective evaluations showed that tactile cues were an effective alternative or enhancement to visual displays. Cross track error was insignificant for both the visually-based SINS and the tactile integrated SINS. The majority of subjects felt that TSAS was easier to

use, provided enhanced navigation, and was preferred over the visual-only display. All divers indicated that operational navigation capabilities could be enhanced with tactile technology.

6.4.3 Uninhabited Marine Vehicles

The use of uninhabited vehicles (UVs) for littoral maritime applications has grown rapidly in the last few years. The design of UVs can be broken down into those which are autonomous, those which are remotely piloted, and those with a degree of autonomy. As with divers operating submersibles, operators of Unmanned Underwater Vehicles can become spatially disoriented. Tactile displays can be utilised for orientation and warning cues, which may enhance orientation by allowing the operator to concentrate on the camera/sensor display. Unmanned Surface Vehicles (USVs) are very similar to boats with enhanced auto-pilot systems. If the USV is equipped with surveillance systems that are monitored by a remote operator, a tactile display can again be utilised for the provision of orientation and warning cues. These potential tactile displays have yet to be field tested.

6.5 SPACE

6.5.1 Orientation Awareness in Microgravity [27, 28]

Summary: This study investigates if an astronaut's orientation awareness can be improved by providing a vibration on the torso that indicates the direction of 'down'. A Tactile Orientation Awareness Support Tool (TOAST) was tested in the International Space Station (ISS). A European Space Agency astronaut performed orientation tasks in different sensory conditions, such as with his/her eyes opened or closed. The main results showed that TOAST improves orientation performance. Task completion was faster, better, and easier with TOAST support, even so when visual cues were available. This case study confirmed the potential of providing orientation information by the sense of touch. Questionnaires used to assess subjective evaluation showed that the tool supported the astronaut in orientation tasks and has potential in challenging situations, but is not needed during daily operations. Although the comfort of the vest was rated as adequate, the somewhat bulky equipment of the demonstrator reduced its wearibility, and changes in body form during microgravity reduced the fit at the upper and lower ends of the vest.

Lessons Learned: Maintaining a good sense of one's orientation in a microgravity environment such as the ISS is difficult because information from the vestibular and the proprioceptive system is lacking. Tactile cues can support orientation awareness.

6.6 CONCLUSION

The experiments presented above form a large body of evidence indicating the potential of tactile displays in a diversity of military applications. Although most studies presented have been proofs-of-concept, favourable effects were found for a wide range of military operators. These include fixed and rotary wing pilots, vehicle drivers, dismounted soldiers, divers, unmanned vehicles, and even astronauts. The positive effect of tactile displays is evident, especially in circumstances of degraded vision or high workload. However, there have not been conducted extended experiments under real operational circumstances and for extended periods (i.e., weeks or months).

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Chapter 7 – TACTILE DISPLAYS IN MILITARY ENVIRONMENTS: CURRENT STATUS AND FUTURE DIRECTIONS

by

J.B.F. van Erp and B.P. Self

7.1 INTRODUCTION

The challenging environments encountered by military personnel require the Human Factors community to constantly search for innovative concepts to improve the interaction between soldiers, equipment, and information. The last 15 years, several groups within NATO started researching the use of tactile displays – displays that use the skin to present information. The primary motivation behind this research is the threat of overloading the eyes, ears and minds of soldiers (whether trained pilots or inexperienced dismounted soldiers) through the ever increasing need to communicate data from information systems. Several theoretical models substantiate the claim that tactile displays can potentially lessen the threat of sensory and cognitive overload. By using the skin as an information channel, a tactile display can reduce the overload of other sensory modalities such as ears and eyes. For example, a localised vibration on the torso can serve as a 'tap-on-the-shoulder' to provide local guidance information. Such information is processed intuitively, which reduces the risk of cognitive overload.

Given the current progress of technological developments and operational concepts regarding the use of tactile displays in military environments, a strong and combined effort of NATO countries was considered important. The NATO RTO HFM Task Group 122 therefore focused on the unique human-system issues associated with effective applications of tactile displays in military environments. Some of the issues included in this report are hardware/actuator technology, perception and psychophysics of touch, interface and coding standardisation, operating concepts, and integration issues.

The often combined efforts of the research groups involved in tactile displays have resulted in a growing body of evidence that tactile displays can indeed be a valuable addition to existing interfaces. Lab studies and several field studies have shown that tactile displays can improve performance and lessen workload. In general, favorable effects were found in the following tasks:

- Navigation;
- Vehicle control;
- Orientation;
- Detecting unexpected events;
- Time critical tasks; and
- Directional warning and attention allocation tasks.

These favourable effects have been noted in the following environments and situations:

- Rotary and fixed wing aircraft, armored vehicles and high speed boats;
- Under Spatial Disorientation evoking conditions;
- Under high G loads and in microgravity;
- During night operations;
- Under high workload conditions;
- In high vibration environments;

- Under water and airborne; and
- During remotely piloted operations (e.g., UAVs).

The successful applications mentioned above are only with regard to military applications – many other tactile displays have been used with automobile driving, gaming and virtual reality, and aids to people with visual impairments. These applications all confirm that tactile displays can be used to greatly improve spatial orientation, navigation, and even communication. The growing interest in other application areas may result in an interesting spin-off and spin-in of knowledge and technology. Recently, several new application domains were added, including sports, gaming, and team coordination.

7.2 FUTURE AREAS OF RESEARCH

Most of the current data on tactile displays have been gathered in controlled lab experiments and relatively simple field studies. The promising results from these trials warrant large scale testing under operational circumstance during prolonged periods. The shared opinion of experts is that the technology is on the verge of introduction into operational environments. Despite this observation, there is also a need to continue work on more fundamental issues that have not been solved yet. Introducing tactile displays into operational environments requires investigating a number of issues.

7.2.1 Coding and Standardization

The algorithm used to code information on the tactile display must be intuitive to the user. Different codings have been used in helicopter hover displays to display virtual corridors and to display self motion. This brings up the question that has been discussed in the visual display community for years – should we use an inside-out or an outside-in display? Although no one has systematically investigated this issue, anecdotal evidence indicates that there is no population preference for one algorithm over the other in the helicopter hover task. The preference is about 50 – 50, which also means that the chosen coding will not be the most intuitive for half of the population. Also, switching between different coding algorithms may result in problems (such as those experienced by pilots that transferred from an outside-in to an inside-out coding of the artificial horizon). This suggests that we should develop a coding that can either be adjusted to user profiles or preferences, or that is standardised across applications, countries and manufacturers.

7.2.2 Limitations of Intuitive Displays and Tactile Clutter

Although the skin is able to process large amounts of information (people who are trained in Braille can actually read with their fingertips), there is a trade-off between the amount of information and the intuitiveness of the tactile signals. Braille reading consumes a large amount of cognitive resources, as does reading with the eyes. That is, a high tactile information transfer rate usually yields codings that are not intuitive and require considerable training. Van Erp introduced the term tactile clutter to describe a situation where displaying multiple signals in parallel on a tactile display results in difficulties interpreting them. Apart from the possible spatiotemporal interaction of individual signals, some form of processing or (spatial) attention may be required to separate the different elements of information, or to track one signal and ignore a second. The limitations to present more complex messages with tactile displays become a relevant issue in, for example, presenting global awareness information. In these situations, it may be beneficial to limit the function of the tactile display to drawing the user's attention to a message or map displayed on a visual display.

7.2.3 Multimodal Integration

A tactile display will rarely be used in isolation, but instead in a combination with visual and/or auditory displays in a multimodal setting. This raises many issues, including how much information will cause

cognitive overload, how to calibrate touch with other modalities in space and time, and how to allocate information to the sensory modalities. In a simple multimodal interaction approach, information would be displayed redundantly via two or even three modalities. In general, this approach may result in faster reaction times and lower workload. A more complex approach than presenting information redundantly is to make the information from the different modalities complementary. In such an approach, there may be costs involved. For example, there are costs involved in switching attention between the different senses.

7.2.4 Hardware Development

Like in any new technology, tactile hardware will need to undergo many iterations before it is available for widespread operational use. Current hardware systems are mostly research oriented, and no hardware that has been field tested is available on a large scale. Developments are required in areas such as miniaturization, weight, cost, power consumption and methods to incorporate tactors into seats, harnesses, and other current equipment. Also, tactor measurement and evaluation protocols should be developed.

7.2.5 Miscellaneous Research Issues

In the previous sections we mentioned several issues (e.g., tactile clutter, multimodal integration, and coding standardization) that were discussed in this report but still require additional research. We can add the following important issues:

- Age-related effects. Most experiments described in this report were run with participants from a relatively young population. However, not all military personnel are below 30 years of age. Important aspects in the design for older users include: thresholds and spatial resolution (in general, the processing of tactile stimuli will degrade with age), learning skin-hand coordination, and trust in the system.
- Psychophysics under different stressors, including high workload and different environmental factors (e.g., extreme temperatures, G-load, vibration).
- Perceiving vibrotactile signals in a vibrating and other stressful environments. Real world applications are closely related to the psychophysical perception in different environmental conditions. There is no systematic knowledge available on tactile perception as a function of real world aspects such as vibrating environments, clothing, pressure, temperature, etc.
- Algorithms to aid the user in switching on the tactile information. Continuous stimulation may result in adaptation and habituation effects, and may even annoy the user. The decision when the display should be switched on then becomes relevant.
- The risk and effects of tunnelling in relation to sensory modality and prolonged use. The use of tactile displays has been suggested as a means to prevent attention tunnelling in the visual and auditory domains. A tactile signal can serve an alerting function to break attentional fixation. There is a risk that with prolonged use of tactile displays, there may also be attention tunnelling. Adaptation and habituation effects may contribute to this, which may cause the user to miss important tactile information.
- Multifunction tactile displays. Tactile displays are primarily designed and tested for one application in isolation. Visual displays are rarely designed for a single function – tactile displays will also usually need to serve more than one purpose. In a multifunction tactile display, the user must be able to discern which function is being displayed. Methods for separating functions in tactile displays (such as sequential separation, spatial separation, sensational separation, and the use of icons and multimodal cues) must be further developed.
- User acceptance. As with any system, user acceptance will ultimately determine the usefulness of tactile displays. The systems must be intuitive, accurate, reliable, and require a minimal amount of

training. Comfort is also a major requirement, particularly since some wearers report that certain tactors can feel ticklish or even annoying. Integration into current equipment is also important, as military members prefer not to don yet another piece of equipment.

7.3 CLOSING REMARKS

Overall, we conclude that data described in this report are important evidence that using the tactile modality in military environments can improve performance and lessen workload, thereby improving the quality and safety of the man-machine-interface and the operational effectiveness of military personnel.

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14. Abstract

This report describes the state-of-the-art of touch-based displays in military environments: neurophysiology, psychophysics, perceptual and human factors issues, hardware and integration issues and lessons learned, and future directions. The document gives an overview of NATO activities and is useful for both end users and designers.

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